CBM in multi-component systems

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To Mitra

Acknowledgements

As I am writing these lines, I look back and see the long road I came. Was it easy? Would I do it again? The answer to these questions is a big NO! Was it worth it? Would I continue doing research? Definitely YES!

I spent 5+ years of my life in writing of this dissertation. During these years, many people supported me to successfully finish this long journey. I am grateful for all of these amazing individuals and would like to thank some of them in particular.

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Javid Koochaki

Eindhoven, July 2012

Contents

List of Abbreviations

ABR	Age-based replacement
AHP	Analytical hierarchy process
ANOVA	Analysis of variance
BR	Block replacement
CBM	Condition-based maintenance
Cc-Cp	Corrective to preventive maintenance cost ratio
CFO	Chance of failure occurrence
CF-PM	Chance of failure occurrence within pm intervals
CM	Corrective maintenance
EG	Economic gain
FMEA	Failure mode and effect analysis
FOS	Federation of systems
FTA	Fault tree analysis
LE	Line efficiency
LOZ	Length of opportunistic maintenance zone
LP	Line productivity
MCDM	Multiple-criteria decision making
MCMT	Mean corrective maintenance time
MPMT	Mean preventive maintenance time
MTBF	Mean time between failure

MTBM	Mean time between maintenance
MTTR	Mean time to repair
N-CBM	Number of components under a CBM policy
PC	Production context
PED	Positive economic dependency
P-F	Potential failure-functional failure
PHM	Prognostics and health management
PM	Preventive maintenance
RCM	Reliability centered maintenance
ROI	Return on investment
RQ	Research question
RM	Risk matrix
TC	Total maintenance costs

CHAPTER 1

Introduction & Research Methodology

In this chapter an introduction to this research will be provided. The concept of condition-based maintenance will be discussed and the research goals and preliminary research question will be explained. A literature review will be conducted that assist us to refine the preliminary question and provides us with logical reasoning about what needs to be done next. Finally, the research methodology and a general summary of the approach used and the outline of this thesis will be presented.

1.1 Background

1.1.1 Maintenance: definition & policies

Maintenance is the combination of all technical, administrative and managerial actions, intended to retain an item in, or restore it to, a state in which it can perform a required function (EN 13306: 2001). In the same standards, a maintenance policy is defined as an interrelationship description between maintenance echelons and indenture levels (subsystem, component) including their maintenance actions.

Maintenance policies are categorized into Corrective Maintenance (CM) and Preventive Maintenance (PM) (Bloch & Geitner 2005, Dhillon 2002). Corrective maintenance (also called run-to-failure) is repairing equipment (or components) after failure has occurred. Preventive maintenance is carried out at predetermined intervals or according to assessment of equipment condition. Preventive maintenance can be time-based or condition based.

Time-based maintenance (also called planned maintenance) involves preventive actions such as inspection, repair, or replacement of the equipment. It is performed in fixed schedules and regardless of the status of a physical asset.

Condition-based maintenance (CBM) is a maintenance policy for equipment components, which is based on the information collected through condition monitoring techniques[1] (Jardine et al. 2006).

CBM is a subdivision of preventive maintenance. It is common both in academia and practice to refer the general term of ‘preventive maintenance’ or PM to time-based maintenance. Throughout this thesis, preventive maintenance and time-based maintenance are used interchangeably.

1.1.2 Paradigm shift in maintenance policies

The rapid development of new technologies has resulted in more complex products which have higher maintenance cost (Jardine et al. 2006). This cost is a significant portion of the operational cost and in some industries (e.g. asset-intensive industries), it accounts for 20–50 % of the production cost (Ben-Daya et al. 2009). At the same time, firms prefer such maintenance services to increase equipment availability rather than to develop an entirely new plant. Hence it is importance to be aware of benefits

[1] The most commonly used techniques are vibration monitoring, thermography, tribology, ultrasonic and visual inspections.

and drawbacks of each maintenance policy and select an appropriate policy that supports these strategic goals.

Time-based maintenance has several advantages over corrective maintenance (run-to-failure) such as minimizing unscheduled downtime, reducing labor costs, and lowering maintenance costs (Wu et al. 2007). However, it does not always eliminate catastrophic failures and may include having to perform unnecessary maintenance activities (Dhillon 2002). These reasons are moving the plant from the traditional choice between corrective and time-based maintenance towards condition based maintenance (Saxena 2007) (see Figure 1-1).

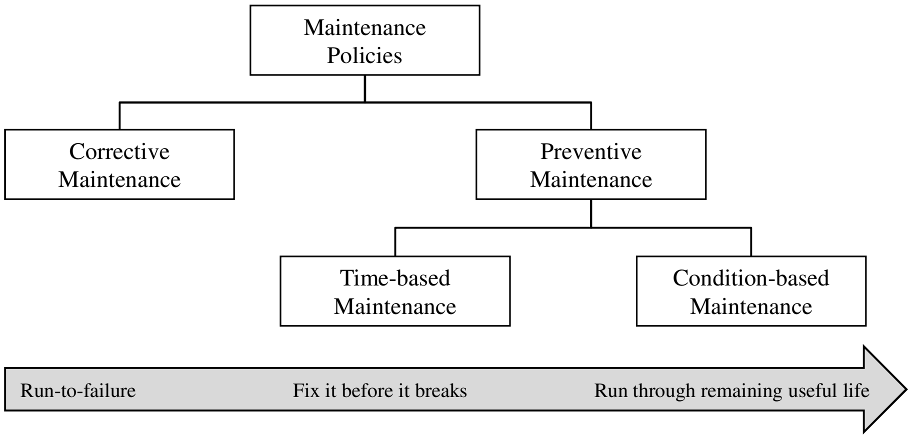

Figure 1-1: Paradigm shift in industrial maintenance (Saxena 2007)

1.2 Research motivation, objective and scope

1.2.1 Motivation

The competitive global market has increased the need for reliable and cost-effective production systems. This has changed maintenance from a ‘necessary evil’ to a business area that requires special attention.

Plants perform maintenance for a number of reasons, such as controlling system availability, increasing production efficiency, meeting internal standards and governmental regulations for safety and environment, etc. Condition based maintenance is one of the policies that can fulfill almost all of the above goals. It is performed to reduce maintenance costs (less unnecessary repairs and replacements leading to less labor and spare parts), improve availability, to reduce (or even eliminate) production losses (due to deteriorated equipment) and to limit damage (less secondary damage)(Starr 1997).

It is interesting to notice that the expected benefits of CBM implementation as reported in the literature contrast with those actually found in practice. According to Mobley (2002), the majority of CBM programmes cannot meet the target return on investment (ROI), between 10 to 12 times of investment, and are not financially justifiable. This has been confirmed in multiple case studies that were conducted in The Netherlands (Veldman et al. 2011a), where the case companies invested considerable time in CBM, with active support from their stakeholders. However, the introduction of CBM did not always cover the envisaged or potential scope. The causes of these limitations in terms of the implementation in most cases related to business aspects instead of to technical aspects (ibid). Companies seem to put a lot of effort in interpreting technical data, while they forget the financial justification of CBM. A good example of this problem has been stated by Mobley (2002):

"After 6 years of a total-plant vibration monitoring program, unscheduled delays had been reduced by about 30 percent. Based exclusively on this statistic, the program was deemed successful, but when evaluated from a standpoint of the frequency of scheduled downtime and annual procurement of maintenance spares, another story emerged. Scheduled downtime for maintenance increased by almost 40 percent and annual cost of replacement parts by more than 80 percent."

To the best our knowledge, the reasons for CBM programmes' failure have not been addressed in the literature. This motivated us to conduct a research project and find the underlying issues behind these failures.

1.2.2 Objective and preliminary research question

The initial goal of this research was to study the reasons of CBM programmes' failure. This goal resulted in the following preliminary research question:

Preliminary RQ: "Why do some CBM programmes fail or why are they not as successful as expected?"

To investigate this question, a literature review (section 1.3) has been conducted. We find that CBM has been mostly studied for a single piece of equipment and that the effectiveness of CBM in a multi-component system has not been thoroughly explored yet in the literature. This may be the reason why some CBM programmes are not as successful as expected. The literature review findings direct us towards a new goal which has become the main theme of this research. In this research we aim to find how CBM behaves in a multi-component environment. It is anticipated that the findings will throw light on this area and assist CBM programmes stakeholders to evaluate this policy in a plant-wide perspective, which constitutes a more realistic framework. To achieve our goal, a set of new research questions have been raised. These questions will be presented in section 1.4.

1.2.3 Research scope

CBM is more complicated than classical (corrective and time-based) maintenance policies. This complication is due to its philosophy and technical difficulties. CBM is only applicable for specific types of equipment, not for all equipment. Therefore, selecting and implementing CBM without analyzing its benefits for the total group of equipment (or components) may result in isolated decisions, which would have a negative impact on the plant's shutdown, production planning and plant's availability. In this perspective, CBM can be viewed as a system in a Federation of Systems (FoS) (Maier 1998). On the other hand, CBM includes technical systems (i.e. OSA-CBM[2] modules) that are operationally independent (Lebold & Thurston 2001). In this research, the focus will be on the role of CBM from operations management perspective (macro level decision processes). Therefore, the technical challenges in design and control engineering are out of scope of this research.

Beside the availability improvement purpose, CBM is implemented for many other non-maintenance reasons. For instance, CBM is used for improving safety, getting ISO certification and lower insurance rates (Mobley 2002). These applications of CBM have their own specific objectives which can make them (financially) justifiable. These non-maintenance applications and their relevant justifications will not be addressed in this research.

1.3 Literature review

The literature review of this research has been conducted in two phases. The first phase of the review was done at the beginning of the PhD project to answer the preliminary research question. The key words used in this phase were quite general and the selection was based on the papers that had been published till 2008. The second phase of the literature review was performed to answer each of the research questions. This phase includes more recent papers that are relevant to the specific topic of each research question.

In the next sub-sections, the finding of the first phase of the literature review is presented. The second phase is presented at the beginning of Chapters 2 to 4.

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[2] OSA-CBM modules: Data acquisition, Data manipulation, Condition monitoring, Health assessment, Prognostics, Decision support and Human interface

1.3.1 Literature selection approach

At the early stage of this research, a literature review was conducted with the aim of finding the potential reasons of CBM programmes failure (i.e. the preliminary research question) and depicting the latest status of CBM in the literature. In an initial attempt to select publications for review, it was found that the majority of papers approach CBM from a technical point of view. This was anticipated due to the nature of the CBM concept. These papers were out of scope of this research. Therefore we only analyzed the papers that view CBM from an enterprise perspective.

The main databases used were ScienceDirect, EBSCOhost, and IEEE XPLORE. 'Condition Based Maintenance', 'Predictive Maintenance' and 'Condition Monitoring' have been used as keywords and as a timeframe the period of 2000-2008 was selected.

A first pre-selection yielded 146 articles. After a closer examination and categorization, 50 publications were selected for final review[3]. The focus has been on refereed journal and conference papers. A detailed discussion of the relevant literature is presented in the next section.

1.3.2 CBM & maintenance concept selection

Various maintenance concept selection tools and frameworks have been introduced in the literature. Selecting CBM, as a maintenance policy, is a result of using these frameworks. Nearly all the papers in this area, state that making decisions on the maintenance concept is a multiple-criteria decision making (MCDM) problem. Therefore the problem is often seen as 'fuzzy' and the selection approach is chosen accordingly. Al-Najjar and Alsyouf (2003a) use fuzzy logic principles to select the most efficient maintenance approach in five stages. The criteria they used were accuracy and effectiveness. Fuzzy techniques for maintenance concept selection were also employed by (Khanlari et al. 2008, Sharma et al. 2005, Wang et al. 2007).

Another popular approach for maintenance concept selection is the Analytical Hierarchy Process (AHP). Bertolini and Bevilacqua (2006) combine goal programming and AHP to select the best strategy for centrifugal pumps. The decision model they develop compares corrective, preventive and predictive strategies on a range of pumps and is able to identify the most suitable concept. Zaeri et al (2007) combine AHP with a statistical tool (factor analysis) using many factors a choice can

[3] See literature review article (Koochaki et al 2008) for complete review.

be based upon (e.g. risk, personnel training, software cost, and reliability). Less technical and more down-to-earth approaches are given by (Dong et al. 2004, Starr 1997, Waeyenbergh & Pintelon 2002). These publications show the wide range of factors that have to be considered when a choice needs to be made. However, they also show that detailed decision rules for concept selection cannot be given when frameworks aims at universal applicability.

To conclude, the majority of CBM justification papers focus on a single piece of equipment and does not consider the 'total plant', which is a fundamental requirement for successful CBM (Mobley 2002).

1.3.3 CBM & planning

In recent years some attempts have been made to optimize CBM planning or link CBM to the production and the master maintenance plan. Due to the nature of CBM, stochastic modeling is extensively used in these papers. For instance in (Amari & McLaughlin 2004) an algorithm to design a CBM model using the Markov chain concept is proposed. Other researchers (Baek 2007) notice the difficulty of a Markovian decision process and simplify the problem through deterministic dynamic programming techniques. Some authors have tried to align CBM with production and inventory management. In Tu et al.(2007), a model-based prognostic process is used to predict the residual life of the equipment, which can be used for spare parts allocation and inventory management. Another paper (Koomsap et al. 2005) proposed an architecture for the use of sensory information of the machine to integrate process control and CBM scheduling. Zhou et al.(2007) tried to integrate a sequential imperfect maintenance policy into Condition-Based Predictive Maintenance (CBPM). Multi-component maintenance models are usually developed for preventive maintenance (Dekker et al. 1997). Only few of these models have considered CBM (Barata et al. 2002, Castanier et al. 2005) in which it is tried to find the optimum inspection time or threshold limits (Marseguerra et al. 2002). Much effort has been put in developing these models and they are valuable. However, considering the stochastic nature of the degradation, the modeling of a CBM easily becomes too complicated. Nevertheless, these theoretical papers generally conclude that CBM is to be preferred over PM and have not studied CBM in a multi-component system and presence of other maintenance polices.

1.3.4 CBM & opportunistic maintenance

The concept of opportunistic maintenance is based on the economic dependency among the components (Rao & Bhadury 2000). The simultaneous maintenance actions are performed by proceeding and/or postponing maintenance activities for individual components, which results in lower maintenance costs. CBM may provide the right information to execute an opportunistic maintenance policy, because CBM provides a time zone in which maintenance activities can be combined. Therefore, opportunistic maintenance could benefit from a well-implemented CBM policy.

It is found that most of the existing papers studied the application of opportunistic maintenance in combination with time-based maintenance policies other than CBM. We found only one paper (Zheng & Fard 1992) that studied a combination of CBM and opportunistic maintenance. In the paper, they propose a hazard-rate tolerance method for an opportunistic replacement policy. In their model, for simplification, the mean time to repair is neglected and it is assumed that all components use the same maintenance policy.

1.3.5 CBM & maintenance resources

Maintenance resources are usually highly skilled and therefore difficult to recruit. These challenges render the efficient and effective use of the scarce maintenance resources very important. This was recognized by other researchers, who have created important insights in this area using analytical modeling, optimization and simulation studies (Ahire et al. 2000, Ait-Kadi et al. 2011, Almeida 2005, Ben Ali et al. 2011, Bertolini et al. 2004, Langer et al. 2010, Martorell et al. 2010, Munoz & Villalobos 2002, Najid et al. 2011, Prosser et al. 1992, Safaei et al. 2008, Suryadi & Papageorgiou 2004). These papers mainly focus on resource allocation and scheduling problems given a particular maintenance policy to determine e.g. the optimum size of the maintenance workforce and the optimum maintenance schedule.

We could not find any paper that studies the interaction of CBM and maintenance resources and workforce planning.

1.3.6 Summary of the literature review

There has been a proliferation of literature on the topic of CBM and condition monitoring in recent years. The number of publications in this area shows industry's interest for implementing this policy. The technical aspects of CBM along with its diverse applications have been covered in academic publications with substantial detail. However, this review has identified certain issues that have not been satisfactorily addressed or have not been addressed at all.

The main goal of this review was to find the reasons of CBM programmes failures. In our review we found only limited scientific research that directly evidenced the failures of CBM programmes. They believe CBM implementations are usually successful in a technical sense, but less successful economically (Lianghua et al. 2009, Mobley 2002, Veldman et al. 2011a).

Researchers have developed different methods for decision making about maintenance concept selection. These methods are mostly designed for an individual piece of equipment rather than for considering operational consequences of implementing CBM. Few attempts also have been made to investigate CBM effectiveness during the implementation phase. It appears that CBM planning is quite difficult due to the stochastic behavior of the technical system and is often even seen as unplannable (Budai et al. 2006). Further, researchers did not consider group maintenance aspects and production context during the CBM selection and implementation phase.

To conclude, there is a gap in the literature regarding CBM evaluation in a plant-wide perspective. The existing CBM evaluation frameworks do often not include the operational consequences of CBM implementation. We believe researching in this area will direct us towards finding the reasons of unsuccessful CBM programmes. We speculate that not evaluating CBM in a multi-component environment is one of the potential reasons for CBM programme failures. It is conjectured that a multi-component environment significantly affects CBM. Implementing CBM for a single piece of equipment may interfere with the group maintenance events and operations of the whole production system that the equipment is part of. Further, the metrics companies use to justify CBM investments do often not include the operational consequences of CBM implementation. These metrics lack the overall view which is needed in the economic justification of CBM. To investigate these, the preliminary research question is refined and a new set of questions is proposed, which comes next.

1.4 Refined research questions

The main objective of this research is to find how CBM behaves in a multi-component environment. To achieve this goal, the problem statement has been split up in several parts resulting in three research questions.

1.4.1 Research question 1

The production context was one of the missing links in the CBM evaluation frameworks. We found this issue has been neglected both in academia and practice. Research question 1 will investigate this criterion.

RQ1: What is the effect of the production context on CBM?

We will answer this question in Chapter 2 and section 5.2. We will make a simulation model to explore the effect of the production context on the investment appraisal of CBM and two alternative maintenance policies.

1.4.2 Research question 2

Our literature review showed that most of the existing papers have not studied how CBM affects group maintenance policies. On the other hand, there is a tendency among maintenance teams to group maintenance events and conduct opportunistic maintenance. This facilitated to define research question 2.

RQ2: Can CBM be effectively applied in multi-component systems using an opportunistic maintenance strategy?

The answer to this question will be presented in Chapter 3 and section 5.3. We modeled a three-component system and analyzed the impact of CBM both in an opportunistic and in a non-opportunistic maintenance context.

1.4.3 Research question 3

It is very important to investigate the situation when companies want to integrate their CBM programmes into their routine maintenance practices. This is immerged in research question 3.

RQ3: What is the effect of CBM on maintenance planning and workforce scheduling?

The answer to this question will explain the potential difficulties in adopting CBM within existing maintenance plans and workforce schedules. This question will be answered in Chapter 4.

1.5 Research approach

To achieve the research goal, it is essential to have a clear research philosophy, strategy and instruments beforehand. In the following sections we discuss the philosophy we applied in the pursuit of the research objectives presented in this thesis.

1.5.1 Research philosophy

Research philosophy concern the nature of reality, what can be known, and how it can be known (Crossan 2003). James et al. (1979) have categorized research philosophies into empiricism and rationalism. The epistemological difference between these two goes back to their positions about the sources of knowledge or source of the justification or warrant required for a statement to count as knowledge (Longworth 2009). Empiricists create knowledge through exploiting of concrete experience and explain universalities from their observations and particulars of experience. Rationalists use logical verification to create knowledge and deny the sufficiency of sensory observations for knowledge creation (Partington 2002).

According to Meredith (1998), rationalism has been the dominant research paradigm in the field of operations management. Also in this particular research we adopted the rationalist position.

1.5.2 Research approach and strategy

The research approach developed by Mitroff et al. (1974) is adopted for this research. In this approach the research cycle contains four main phases, namely conceptualization, modeling, model solving and implementation. Research can arguably begin and end at any of the phases in the cycle, based on the selected strategy and goals, provided that the researchers being aware of the claim they made. However, when describing modeling efforts, it is convenient to let conceptual models precede scientific models.

Bertrand and Fransoo (2002) classify quantitative (model-based) operations management research into *empirical (descriptive, normative)* and *axiomatic (descriptive, normative)* types. We selected axiomatic normative strategy for our study. In this strategy, *"knowledge about the behavior of certain variables in the model is based on assumptions about the behavior of other variables in the model. It may also produce knowledge about how to manipulate certain variables in the model, assuming desired behavior of other variables in the model, and assuming knowledge about the behavior of still other variables in the model"* (ibid).

In the axiomatic strategy, analysis of a quantitative scientific model (model solving) is the central process and the conceptual models are mostly built on previous comparative research. In our study, we made our conceptual models based on the existing models in the literature. For the scientific modeling we used a computer simulation tool and validated it through a hermeneutic approach (Kleindorfer et al. 1998). In the next sections we explain our research instrument and validation in detail.

1.5.3 Research instrument

According to Robinson (2004), simulation is *"experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time, for the purpose of better understanding and/or improving that system"*. The rapid development of IT industry and the appearance of new software packages have increased the application of this methodology. Simulation modeling may lead to better and faster decision-making, more accurate predictions, and the ability to perform "what-if" analysis to support analyses.

Simulation is used in many contexts for insight gathering, problem-solving, controlling real-time processes, training etc. The application of simulation modeling ranges from natural systems in physics, chemistry etc. to human systems in economics as well as engineering (Banks et al. 2009). Simulation is also one of the common methods in operations management and maintenance engineering and widely used to solve the complicated models in these areas.

Computer simulation has been chosen as the main research instrument in this study. This instrument helps us to cover the existing limitations of current mathematical models and to investigate the research objectives more accurately. There are several reasons why simulation is preferred to other (i.e. analytical) modeling approaches (Robinson 2004):

1) Modeling variability is one of the main advantages of simulation modeling over other modeling techniques such as linear programming, dynamic programming, simulated annealing, etc. Many of these methods are not able to sufficiently model variability (if they are already adapted to account for variability, their complexity increases dramatically). The stochastic nature of the degradation is one of the main reasons that make the analytical modeling of the CBM policy more complex.

2) Simulation requires fewer assumptions than many other modeling approaches. For instance, for simplification, many other models use an exponential distribution for components' failure function.

3) The model workings and its results are often more transparent in simulation than with mathematical equations, due to the visual display capability of the simulation tool. This specifically becomes more important when it is used for an insight gathering purpose.

As mentioned in Bertrand & Fransoo (2002), model parameters have a significant impact on the quality of the results. Model's data can be categorized into three types based on their availability and collectability (Robinson 2004): 1) Data are available; 2) data are not available but collectable; 3) data are not available and not collectable. Our models data are placed in the latter type. Estimation and treating the data as an experimental factor are the two ways that have been suggested to treat this type of data (ibid). Both methods have been used in this study. The model characteristics are built upon the previous researches. We carefully defined our parameters (fixed, variable) and designed the experiments.

The computerized models were developed in Plant Simulation (previously Emplant) software[4] . The results are presented and interpreted through statistical techniques (e.g. analysis of variance).

1.5.4 Model verification & validation

Verification and validation are two important qualifications that create enough confidence in a model for the results to be accepted (Robinson 2004). According to (Pegden et al. 1995): "*Verification is designed to see if we have built the model right, whereas validation is the process of determining that we have built the right model*".

To verify the models, we used several techniques that has already been introduced in the literature (Banks et al. 2009). At first, flow logic diagrams have been made and the events occurrence has been checked with them. Further, we used tracing and debugging techniques (Banks et al. 2009) to examine whether the model outputs are reasonable or not. For this purpose, software features for debugging are used. Finally, the models have been examined by another researcher than their developer.

In this research, a hermeneutical approach (Kleindorfer et al. 1998) is opted for validity of our the models. In this approach, the model builder is free to increase the credibility of the model through any reasonable means (e.g. model users and referees of journal articles) (ibid).

1.5.5 Thesis outline

This thesis consists of six chapters. The main body of this thesis (Chapters 2, 3 and 4) is based on the articles that are either published, accepted for publication or under review at peer reviewed journals. These chapters can be read as individual pieces of research. For this reason, the introductory sections of these chapters (which may be repetitive) are kept as they are in the original articles. By the same reasoning, additional experiments for Chapters 2 and 3 are presented in a separate chapter (i.e.

[4]Plant Simulation is an object oriented tool which is developed by Siemens PLM software company and is used for discrete event simulation.

Chapter 5). The following briefly outlines the chapters; corresponding articles and focus (see Figure 1-2).

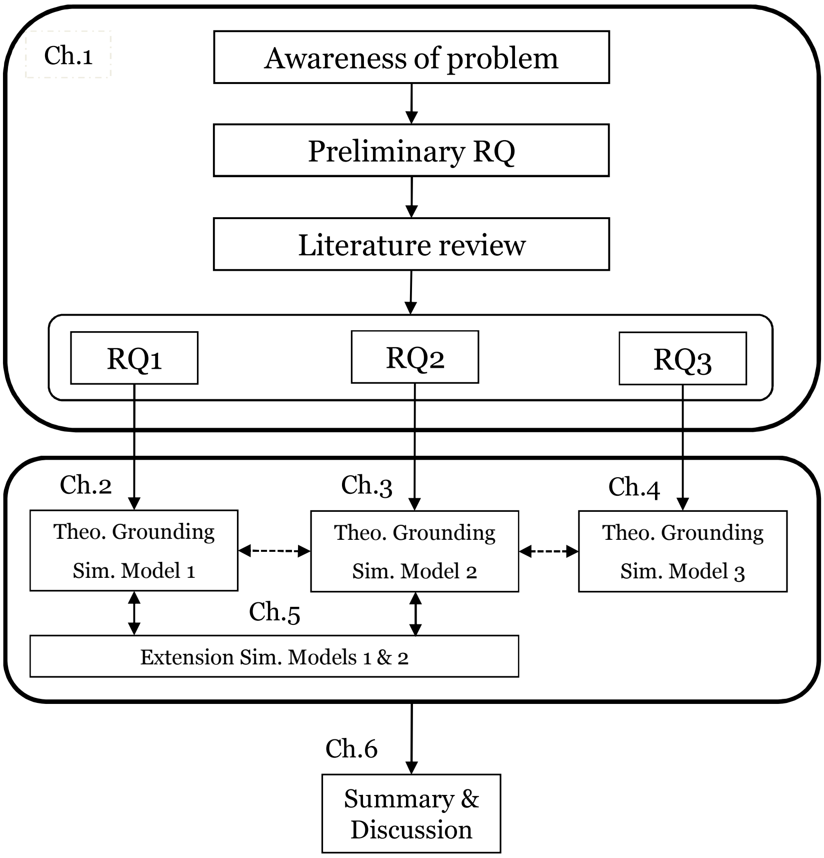

Figure 1-2: Thesis outline

Chapter 2

This chapter will study maintenance policies on a system of two components in series. It will focus on the effectiveness of CBM and will highlight the role of the production context and the importance of using appropriate metrics to assess this maintenance policy.

Corresponding manuscript: "Koochaki, J., Bokhorst, J.A.C., Wortmann, J.C., & Klingenberg, W. 2011b. Evaluating Condition Based Maintenance effectiveness for two processes in series. *Journal of Quality in Maintenance Engineering*, 17, (4) 398-414".

Chapter 3

In this chapter we will examine the impact of opportunistic maintenance on the effectiveness of CBM. We simulate a three-component system in series and vary the number of components under a CBM policy, the length of the opportunistic maintenance zone, the cost benefits of grouping maintenance activities, and the chance of a failure occurrence within a PM interval.

Corresponding manuscript: "Koochaki, J., Bokhorst, J.A.C., Wortmann, J.C., & Klingenberg, W. 2011a. Condition based maintenance in the context of opportunistic maintenance. *International Journal of Production Research,* forthcoming".

Chapter 4

In this chapter will study the impact of using CBM in serial and parallel multi-component systems with different types of maintenance resources and their associated limitations. We will simulate a system consisting of three components for three situations: (1) a situation without worker constraints, (2) a situation with a single internal maintenance worker, and (3) a situation with external maintenance workers with a significant response time.

Corresponding manuscript: "Koochaki, J., Bokhorst, J.A.C., Wortmann, J.C., & Klingenberg, W. 2012. The influence of Condition Based Maintenance on workforce planning and maintenance scheduling, *International Journal of Production Research,* (under review)".

Chapter 5

In this chapter additional experimental factors are analyzed as extensions to Chapters 2 and 3.

Chapter 6

This chapter will reflect the summary of the results that have been found throughout this research. Finally we will end the thesis by recommending areas, issues and directions for future research.

CHAPTER 2
The effect of production context on CBM

This chapter will study maintenance policies on a system of two components in series. It will focus on the effectiveness of CBM and will highlight the role of the production context and the importance of using appropriate metrics to assess this maintenance policy.

This chapter is based on the following manuscript:

Koochaki, J., Bokhorst, J.A.C., Wortmann, J.C., & Klingenberg, W. 2011b. Evaluating Condition Based Maintenance effectiveness for two processes in series. *Journal of Quality in Maintenance Engineering*, 17, (4) 398-414

2.1 Introduction

Maintenance plays an important role in the production systems' efficiency. Maintenance systems can have a large impact on the profit of a plant and selecting appropriate maintenance policies is vital for each manufacturing company. Traditionally, maintenance policies are grouped into two main streams: corrective and preventive maintenance. Corrective Maintenance (CM) is a policy in which equipment is repaired after a failure has occurred. In Preventive Maintenance (PM), maintenance actions are performed based on a fixed schedule or when equipment reaches its predefined age limit. The literature presents various advantages and disadvantages of these two policies (Marquez 2007, Nakagawa 2005). Condition-Based Maintenance (CBM) is a subdivision of preventive maintenance (Bloch & Geitner 2005). It utilizes the operating condition of equipment to predict a failure event. The goal of this policy is to prevent any unplanned downtime and to minimize maintenance cost by avoiding unnecessary preventive actions (Moubray 1997).

The rapid development of industries and competitive global markets has increased the need for reliable and cost-effective production systems. Accordingly, companies are forced to increase the investment in their maintenance systems. These investments can be in terms of significant resources assigned to maintenance departments and the adoption of new concepts and technologies such as Condition-Based Maintenance, or Prognostics and Health Management (PHM) systems (Waeyenbergh & Pintelon 2002). In the capital intensive industries, like the process industry, these investments are even higher. In this industry, unplanned downtime costs up to 250,000 dollars per hour and CBM has been introduced as a policy to eliminate unpredicted failures and enhance profitability (Mayall 2007).

However, despite the fact that companies invest a lot in CBM, there is evidence that CBM is not always successful in practice (Koochaki 2009, Mobley 2002, Veldman et al. 2011a). CBM implementations are usually successful in a technical sense, but less successful economically (Lianghua et al. 2009). We conjecture that the metrics companies use to justify CBM investments do often not include the operational consequences of CBM implementation. The metrics used may show potential improvements in parameters like availability for each piece of equipment, while the actual production line efficiency will decrease. The metrics used mainly focus on a single piece of equipment and lack the overall view which is needed in the economic justification of CBM. We use simulation in order to include the system-wide operational consequences of CBM in more elaborate metrics for CBM justification.

The remainder of this chapter is organized as follows. Section 2.2 reviews the literature on CBM. Section 2.3 starts with some evidence from practice and ends with our hypothesis and the objectives of this chapter. Section 2.4 explains the simulation methodology used and section 2.5 describes the system configuration, experiments and model parameters. The results are presented and discussed in section 6. Finally the summary and conclusions are presented in section 2.6.

2.2 Literature review

The area of plant maintenance has received considerable attention from various scholars. This is particularly so after the 1960s and Barlow's work on preventive maintenance policies (Barlow & Hunter 1960). Many mathematical models have been developed and preventive maintenance has been studied from different angles (Budai et al. 2006, Cho & Parlar 1991, Dekker 1996, Garg & Deshmukh 2006). Similarly, Condition-Based Maintenance, as a subdivision of preventive maintenance, has been widely researched. These studies can be grouped into three literature streams.

The first stream of publications has focused on the technical side of CBM. Here, various CBM techniques such as vibration monitoring, oil analysis, thermal imaging, ultrasonic testing, etc. have been studied. Also, a range of methods has been introduced to more accurately identify and predict machine failures. The papers in this stream are usually published in the engineering journals and they usually do not consider the business aspects of CBM. A number of literature surveys (Han & Song 2002, Jardine et al. 2006, Kothamasu et al. 2006) show the plethora of papers in this area. A main conclusion is that CBM is in principle technically feasible in many production units of plants in various industries.

The second stream of publications can be found in the area of computer and information science. In these papers, different architectures of CBM systems as well as various protocols to exchange data or information have been proposed. For instance, some authors e.g. Tsang et al. (2006) suggested to construct a proportional hazards model based on the gathered data from maintenance events, condition monitoring, and installation data. Nikolopoulos et al. (2003) tried to integrate maintenance within an ERP system. These papers demonstrate that CBM often requires ICT investments and that these investments contribute to improved asset management.

In the third stream of publications on CBM, various mathematical models and decision making tools are developed. Stochastic models are extensively used in this category. Amari & McLaughlin (2004) used an algorithm to design a CBM model using the Markov chain concept. Baek (2007) noticed the difficulty of a Markovian decision process and simplify the problem through deterministic dynamic programming techniques. Some authors have tried to align CBM with production and inventory management. Tu et al. (2007) developed a model-based prognostic process to predict the residual life of the equipment, which can be used for spare parts allocation and inventory management. Koomsap et al. (2005) proposed an architecture for the use of sensory information of the machine to integrate process control and

CBM scheduling. Zhou et al. (2007) tried to integrate a sequential imperfect maintenance policy into Condition-Based Predictive Maintenance (CBPM). Multi-component maintenance models are usually developed for preventive maintenance (Dekker et al. 1997). Only few of these models have considered CBM (Barata et al. 2002, Castanier et al. 2005) in which it is tried to find the optimum inspection time or threshold limits (Marseguerra et al. 2002). Much effort has been put in developing these models and they are valuable. However, considering the stochastic nature of the degradation, the modeling of a CBM easily becomes too complicated. Nevertheless, these theoretical papers generally conclude that CBM is to be preferred above PM and other policies.

In contrast with traditional preventive and corrective maintenance policies, CBM implementation requires initial investments and personnel training. Further, "total plant optimization" is a fundamental requirement for successful CBM programmes (Mobley 2002). Therefore, CBM justification can be regarded as a plant-wide decision. However, the majority of CBM justification papers focuses on a single piece of equipment and does not consider the production context to justify CBM. For example, Bertolini & Bevilacqua (2006), combined goal programming and AHP was applied to select the best strategy for centrifugal pumps. The developed model compares corrective, preventive and predictive strategies on a range of pumps and is able to identify the most suitable concept for pumps. As another example,(Al-Najjar & Alsyouf 2003b) used fuzzy logic principles to select the most efficient maintenance approach for a single piece of equipment in five stages. Similarly, a practical and comprehensive framework for single pieces of equipment was proposed by Waeyenbergh & Pintelon (2002). Other papers specifically focus on CBM technology selection. For instance, Carnero (2005) proposes combining AHP and factor analysis as a method for diagnostic tool selection. Hess et al.(2001) identify different CBM techniques and use two sets of criteria (i.e. technology effectiveness and cost effectiveness) to arrive at a technological decision. To conclude, the CBM justification papers typically focus on maintenance costs, machine availability, or both. Furthermore, they do not consider the "total plant", or in other words, the production context.

2.3 CBM in practice

Maintenance is a supporting function in an organization. Plants perform maintenance for a number of reasons, such as controlling system availability, increasing production efficiency, maintaining quality and meeting governmental regulations for safety and environment. These objectives have different priorities in various industries. In the process industry, the operations are continuous or in batches and they require large and expensive equipment (Fransoo & Rutten 1994). Ensuring high availability of this equipment in an economical optimal way has the highest priority in this industry (Arts et al. 1998). Moreover, the performance of the typical equipment used in the process industry, like pumps, fans, compressors, etc. are negatively affected by mechanical degradation. These characteristics make CBM an ideal maintenance policy for the process industry.

In practice, Reliability Centered Maintenance (RCM) (Moubray 1997) is the common method for justifying CBM. In the RCM method, CBM is advised when all the following three conditions apply: 1) failures have an adverse effect on safety, availability, quality, etc., and 2) it is technically feasible to detect a failure before its occurrence, and 3) it is financially justifiable. For the first two conditions, this approach uses failure mode and effect analysis (FMEA), fault tree analysis (FTA), and risks matrix (RM). These tools are used to identify failure modes, their causes and consequences. For investigating the third condition, companies usually use availability, system safety, and initial investments as inputs for calculating financial justification. These metrics are useful, but they do not show the whole picture. Operational consequences due to failure are difficult to calculate and are usually missed. This issue is in line with empirical findings (Muchiria et al. 2009) which show a lack of direct alignment between maintenance objectives and KPIs.

According to Mobley (2002), the majority of CBM programmes cannot meet the target return on investment, between 10:1 and 12:1, and are not financially justifiable. This has been confirmed in multiple case studies that were conducted in the Netherlands (Veldman et al. 2011a). The case companies invested considerable time in CBM, with active support from their stakeholders. However, the introduction of CBM was not a success. The causes of these implementation failures related mostly to business aspects instead of to technical aspects (Lianghua et al. 2009). Companies seem to put a lot of effort in interpreting technical data, while they forget the financial justification of CBM. A good example of this problem has been stated in (Mobley 2002):

> *"After 6 years of a total-plant vibration monitoring program, unscheduled delays had been reduced by about 30 percent. Based exclusively on this statistic, the program was deemed successful, but when evaluated from a standpoint of the frequency of scheduled downtime and annual procurement of maintenance spares, another story emerged. Scheduled downtime for maintenance increased by almost 40 percent and annual cost of replacement parts by more than 80 percent."*

It is interesting to notice that the expected effects of CBM implementation as reported in the literature contrast with those actually found in practice. We believe that the implementation of CBM for a single piece of equipment may interfere with the operations of the whole production system that the equipment is part of. A too narrow focus at the time of investment appraisal may therefore be a reason for the contrast found. In our view, in order to evaluate CBM programmes, all the obtained costs and benefits associated with implementing these programmes should be quantified in a plant wide perspective. In this chapter, we will explore these effects of the production context on the investment appraisal of CBM and two alternative maintenance policies.

2.4 Methodology

Maintenance activities do not only affect the availability of a single piece of equipment, but they also have a significant impact on the efficiency of the overall production system. To be able to study this effect, a whole plant (or a complete unit) has to be modeled instead of a single piece of equipment. Since it is not feasible to model a complete plant with all its equipment in all possible configurations, a first step would be to select a small serial production system consisting of two pieces of equipment or processes. This is a common configuration in the process industry. To solve the model analytically, we have to consider too many assumptions which make the model too complex or even insolvable.

Simulation is widely used in reliability engineering and maintenance to solve complicated problems (Andijani & Duffuaa 2002, Duffuaa et al. 2001). In this study we used simulation modeling. The simulation model is developed using Tecnomatix Plant simulation software[5]. The models have been verified by comparing event occurrences with flow logic diagrams, tracing and debugging (Banks et al. 2009) and validated through analytical techniques. The results are analyzed through analysis of variance (ANOVA).

[5] www.siemens.com/plm

2.5 System description and model development

The system under study is a serial production system consisting of two pieces of equipment or processes. The circles show the pieces of equipment/processes and the triangles represent the buffers. The inputs arrive in the system, are transformed sequentially and leave the system as finished output (see Figure 2-1). The processes are identical and can be fully utilized (100%) in the ideal situation.

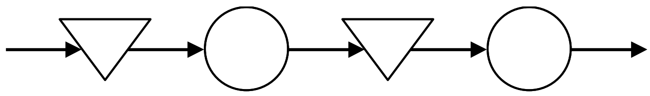

Figure 2-1: System configuration

The following assumptions have been considered in developing the model:

i. The input material is infinite (the first process is never starved);
ii. Any maintenance activity will change the condition of a piece of equipment to as-good-as-new;
iii. A group maintenance concept has not been included in the model. Therefore, failure of a single piece of equipment does not have any effect on the maintenance schedule of the other piece of equipment;
iv. It is technically possible to implement CBM for the equipment used;
v. Transport times of goods to and from the two processes are neglected.

Next we will further describe the simulation model by distinguishing the fixed and experimental factors and by addressing the performance indicators.

2.5.1 Fixed factors

The production system produces 24 hours a day seven days a week. It only stops when a random failure happens (which requires corrective maintenance) or when preventive maintenance is carried out. A fixed Mean Time To Repair (MTTR) of 12 hours is modeled for preventive maintenance as well as for corrective maintenance. The preventive maintenance cost is set at 150 euros. The cost includes man-hour expenditure, shipping cost of the spare part and other indirect costs due to performing maintenance activities. In corrective maintenance, failure occurrence is unpredicted and reducing line stoppage requires an immediate action. Therefore, a higher cost is incurred to replace the component. In the model, the corrective maintenance cost is considered to be twice the amount of preventive maintenance cost. Accordingly, the effect of MTTR has thus been transferred to the maintenance costs therefore.

We assume that the occurrence of equipment failures is distributed according to a gamma distribution with a mean of $\mu = \alpha\beta$ and a variance of $\sigma^2 = \alpha\beta^2$ in which α is the shape and β is the scale parameter (see formula 2.1). This distribution is widely used to model failure functions both in the literature as well as in successful maintenance applications in industry (Castanier et al. 2005, Grall et al. 2002, Van Noortwijk 2009). Since the probability of failure increases as time progresses, the gamma distribution can represent the ageing of equipment and can thus be used in the modeling of preventive maintenance and condition-based maintenance concepts.

$$g(x;\alpha,\beta) = \frac{\beta^{\alpha}}{\Gamma(\alpha)} x^{\alpha-1} e^{-\beta x} \text{ for } x > 0 \qquad (2.1)$$

2.5.2 Experimental factors

We consider three experimental factors: (1) the type of maintenance policy used, (2) the production context, and (3) the chance of a failure occurrence within a PM interval. The first factor is to compare CBM with alternative maintenance policies. The second factor investigates the impact of the production context, in particular the size of the buffers. We look at CBM effectiveness for loosely coupled processes and tightly coupled processes. Finally, the third factor indicates the sensitivity of the relation between the failure distribution and the PM interval. Insight in this relation enables to us to compare CBM with alternative PM policies more precisely.

In addition to the experimental factors mentioned above, two new factors are introduced, experimented with and analyzed in section 5.2. This extends the research of the paper this chapter is based on.

2.5.2.1 Maintenance policies

In this chapter, CBM is compared with two main approaches used in preventive maintenance, namely Block Replacement (BR) and Age-Based Replacement (ABR). As previously mentioned, CBM is carried out based on diagnostic tests or other condition monitoring techniques. Under CBM, we assume that any failures that will happen are noticed earlier and are treated as preventive maintenance at their occurrence. CBM is thus ideal in our model, since there will be no need for corrective maintenance.

Block replacement (or constant interval replacement) is one of the commonly used replacement policies in practice. In this policy, components are replaced in a fixed schedule (i.e. at fixed times), and at failures (Marquez 2007). The replacement activities in the fixed schedule can be regarded as preventive maintenance, the replacement activities at failures are regarded as corrective maintenance. The policy is popular due to its ease of use in assets maintenance scheduling. In our simulation, a new PM activity for BR is scheduled 60 days after the previous PM activity has finished.

ABR resembles BR, but the difference is that when corrective maintenance has been performed, the next PM activity is reset and scheduled after a fixed period of time (ibid), which we set again at 60 days. In ABR, breakdowns thus impact the PM maintenance schedule. Any unpredicted failure in ABR postpones the next PM activity. The interval thus starts after any maintenance activity (i.e. preventive or corrective) and ends either with a failure or with a PM activity, whichever occurs first. This means that the schedule is constantly changing, which makes ABR a dynamic policy. Also, the total number of PM actions in the long term will be less than BR. One would expect this to make ABR more efficient than block replacement.

2.5.2.2 Production context

In our model, we study the impact of production context by studying loosely coupled and tightly coupled processes. The loosely coupled processes are more or less independent, and therefore show resemblance with the single piece of equipment cases described in the literature. By contrast, the two tightly coupled processes are fully dependent, since there is no storage between these two processes. We assume that a plant wide perspective is particularly required for the production context of the coupled processes.

2.5.2.3 Chance of failure occurrence within PM intervals

In preventive maintenance planning, the main challenge is to define the optimum maintenance intervals. Short intervals increase preventive maintenance costs. Contrarily, long intervals boost the chance of failure occurrence and subsequently increase corrective maintenance costs. To compare CBM with preventive maintenance policies like BR and ABR, it is important to be aware of the optimality of the PM intervals and the chance of failure events within those periods.

To address the above issue and reflect the accuracy of the PM intervals, α and β are initially defined such that there is a 5% probability of a failure occurring within the PM interval. This reflects the first level of this experimental factor. Then the shape is kept and the failure function shifted to the left, which increases the chance of failure to 15% (second level) and 30% (third level). Table 2-1 gives an overview of all experimental factors with their levels (including abbreviations that will be used hereafter).

Table 2-1: Overview of experimental factors and levels

PL Maintenance policy	BR Block Replacement	ABR Age-Based Replacement	CBM Condition-Based Maintenance
PC Production context	Loosely coupled	Tightly coupled	
CFO Chance of failure occurrence	5%	15%	30%

2.5.3 Performance indicators

The majority of plants use total maintenance cost and availability to measure the maintenance performance (Lofsten 2000). In our simulation study, we use the same indicators and include line efficiency as an additional indicator to more accurately show the effects of the production context.

2.5.3.1 Total maintenance cost

Total maintenance cost is the summation of the annual corrective maintenance and preventive maintenance costs. Each preventive maintenance activity costs 150 euros and each corrective maintenance activity costs 300 euros. In our cost calculation, product quality issues such as startup losses, defects or rework costs are not included. Further, since the initial investment of a CBM programme just has a predictable offsetting effect on the total maintenance cost, it is not included in the calculation. Moreover, we have not assigned any cost for product storage and equipment's' idle time. Therefore, total maintenance costs will not be affected by the production context, only by the policy used and the chance of failure occurrence.

2.5.3.2 System availability

Achieved availability (A_a) is used to calculate system availability. In the calculation of achieved availability, both corrective and preventive downtimes are considered (Sherbrooke 2004) (see formula 2.2).

$$\%A_a = \frac{MTBM}{MTBM + MCMT + MPMT} \times 100 \qquad (2.2)$$

MTBM is the mean time between maintenance, MCMT is the mean corrective maintenance time, and MPMT is the mean preventive maintenance time.

Achieved availability is widely used in industry and measures the hardware reliability of the equipment. System availability for two processes in series is calculated as the product of the achieved availability of the two single pieces of equipment. Logistical issues (e.g. spare parts availability) and the production context do not have any effect on the calculation of achieved availability and system availability (ibid).

2.5.3.3 Line Efficiency (%)

Line Efficiency (LE) is used to indicate the impact of the production context on the effectiveness of a policy. This indicator is defined by Buzacott (1967), to study the role of buffer stocks in serial processes. Each process can be in an operating status, a break down status or a forced down status. Operating means that the process is carrying out its function and inputs flows through the process. A breakdown status happens when a process/equipment is down due to maintenance activities. Finally, a forced down status means that the process is in working order, but cannot operate due to line blockage or starvation. Blocking happens when the upstream process is ready but cannot release output to the downstream process because the downstream process is not ready. Starvation happens when the downstream process is ready to work but no output is released by the upstream process to work on.

Line efficiency is calculated as the ratio of the aggregate time the process in an operating status over the total time. Under tightly connected processes, the efficiency is the product of the efficiency of each individual process (E_i). Under loosely coupled processes (with infinite buffer), the efficiency is the minimum efficiency of the two processes. This performance indicator is quite similar to the operational availability concept as explained in (Sherbrooke 2004). However, instead of incorporating a delaying time for spare parts, the indicator here considers blocking and starvation of equipment. In our model, blocking only happens for the first (upstream) process and starvation only for the second (downstream) process. Including blocking and starvation provides a more comprehensive insight in the effectiveness of the policies considered (see formulas 2.3, 2.4, 2.5).

$$\% E_i = \frac{\text{Operating time}_i}{\text{Operating time}_i + \text{Break down time}_i + \text{Forced down time}_i} \times 100 \tag{2.3}$$

$$\%LE_{\text{(Tightly connected processes)}} = \prod_{i}^{n} \% E_i \quad , i = 1, 2...n \tag{2.4}$$

$$\%LE_{\text{(Loosely connected processes)}} = \text{Min}\,(E_i)\,, i = 1, 2...n \tag{2.5}$$

2.6 Results and Discussion

Eighteen experiments (three policies x two degrees of coupling x three chances of failure occurrence) were performed. To gain statistically reliable results, each experiment consists of 40 runs. Accordingly, each run was carried out with different seeds to create maximum independence. Each run was simulated for 3650 days after a warm up period of 730 days. We used separate Analyses of Variance (ANOVAs) to analyze the effects on total maintenance cost, system availability and line efficiency. Post hoc tests (i.e. Tukey's range tests) were carried out as a follow up.

In our analysis we will first focus on total maintenance costs and system availability. These two performance indicators are typically used in practice. The results will show how a CBM programme is usually justified. Thereafter we will focus on line efficiency, which will show a pitfall in CBM programmes evaluation.

2.6.1 Total maintenance cost and system availability

Table 2-2 shows the ANOVA results for maintenance policy (PL) and chance of failure occurrence (CFO) as independent variables and total maintenance cost and system availability as dependent variables. Since the production context has no effect on these two performance indicators, it is not included as an independent variable. The ANOVA reveals that both independent variables and their interaction significantly affect maintenance cost and system availability (using $\alpha = 0.05$).

Table 2-2: ANOVA results of the stage one

Source	Total maintenance cost		System availability	
	F	p- value	F	p- value
PL	4556,3	< 0,001	6380,0	< 0,001
CFO	2489,5	< 0,001	1699,4	< 0,001
PL*CFO	541,8	< 0,001	681,2	< 0,001

2.6.1.1 Total maintenance cost

PL, CFO, and their interaction (PL x CFO) significantly affect the total maintenance cost. PL seems to have the largest effect (F value of 4556.3). CBM performs best with respect to the total annual maintenance cost (with the lowest cost of 1681.8 euros). BR performs worst with a total annual cost of 2390.8 euros, while ABR is placed in between BR and CBM. This result is quite predictable and in line with the theory. According to Barlow & Proschan (1996), ABR is more efficient than BR. Due to the fact that in ABR the PM intervals are reset when a failure occurs, the preventive maintenance cost in ABR will be less than in BR. In the model, we assumed that CBM is ideal, meaning that no preventive maintenance activities are scheduled and failure events are treated as preventive maintenance activities. Therefore, CBM can be viewed as a special type of ABR in which we are able to eliminate all CM costs.

CFO also has a significant effect on the total cost. When CFO increases from 5% to 30%, the number of corrective maintenance actions within PM intervals will increase. This subsequently increases the total maintenance cost by nearly 29% (from 1818.0 to 2341.0).

The interaction of CFO and PL shows that CFO affects the maintenance costs differently for the various policies (see Figure 2-2), CFO significantly affects the total annual maintenance costs for BR, while it is less influential for CBM. The difference in annual maintenance costs between a CFO of 5% and 30% is 959 euros for BR and 116 euros for CBM.

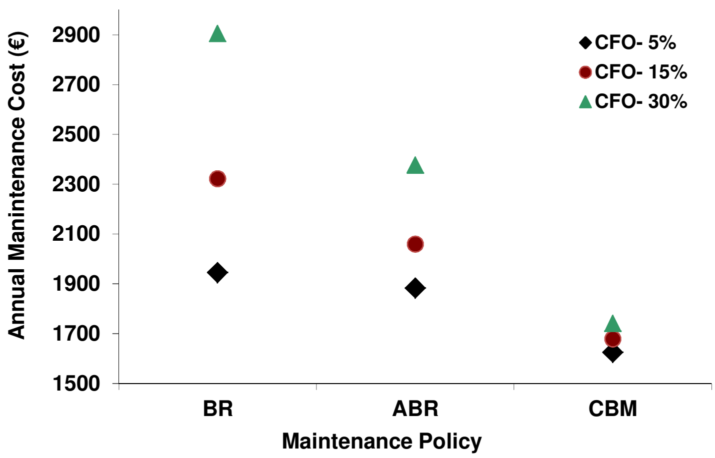

Figure 2-2: Policy - CFO interaction effect on total annual maintenance cost

2.6.1.2 System availability

PL, CFO, and their interaction (PL x CFO) significantly affect system availability. The main effect of PL shows that CBM provides the highest availability (98.47%) and BR the lowest (98.14%). The number of failures and PM activities and the associated repair times have a direct effect on system availability. As expected, the number of scheduled PM activities in BR is larger than that in ABR. This means that more MPMT has to be added to the denominator in formula 2.2, which implies lower system availability. The same reasoning can also be used to explain the effects seen with CBM. Since we assumed no unpredicted failure in CBM, we would have less cumulative MPMT in any given period. Besides, in CBM, the preventive maintenance actions are done when the equipment reaches its degradation threshold (AKA 'hard life' (Knezevic 1993)). This threshold is usually longer than the PM intervals defined by ABR and BR. Hence, CBM performs better than BR and ABR with respect to system availability.

CFO has a negative effect on system availability. By increasing CFO, the system's downtimes increase, which results in a lower system availability. The highest availability (98.40%) was achieved when the CFO was 5%; the lowest availability (98.23%) was reached when CFO was 30%.

The interaction of PL and CFO shows that CFO has a minimal effect on availability in ABR, a larger effect in CBM, and the largest effect in BR (see Figure 2-3). In ABR, the PM interval is reset after any maintenance actions (corrective or preventive). This explains why CFO does not have much effect on this policy. Conduction of simple main effects of CFO using Sidak adjustment clarified that the difference between 5% and 15% CFO in ABR is not statistically significant.

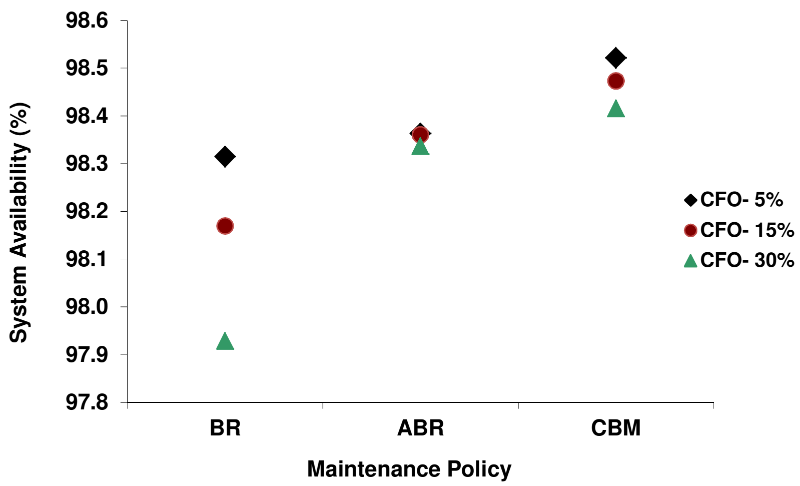

Figure 2-3: PL - CFO interaction effect on system availability

The results for system availability and total maintenance cost show that CBM performs better compared to ABR and BR. These traditional performance indicators are usually used to justify CBM programmes. In the next section, we analyze the results for line efficiency and demonstrate that using a comprehensive metric affects the justification of CBM programmes.

2.6.2 Line efficiency

Table 2-3 shows the ANOVA results for maintenance policy (PL), production context (PC) and chance of failure occurrence (CFO) as independent variables and line efficiency as dependent variable. All independent variables and their interactions significantly affect line efficiency (using $\alpha = 0.05$).

Table 2-3: ANOVA results

Source	Line efficiency	
	F	p- value
PL	2850,03	< 0,001
PC	128862,02	< 0,001
CFO	704,47	< 0,001
PL*PC	5200,15	< 0,001
PL*CFO	213,99	< 0,001
PC*CFO	261,44	< 0,001
PL*PC*CFO	61,25	< 0,001

The production context influences line efficiency most. In the loosely coupled scenario, products are stored in the buffer when there is a maintenance action at the downstream process. Therefore, there will be no blockage in the line. Similarly, there is only a small chance for starvation at the second machine. This only happens if the buffer is empty, the first process is in failure and the second process is ready to operate. The experiment results for the loosely coupled scenario were as expected. Since there was virtually no blocking and starvation (0% and 0.01%, respectively), the efficiency of each individual process (E_i) closely resembled the achieved availability. With loosely coupled processes the line efficiency shows the same pattern as system availability and the percentages basically only differ due to the fact that LE is the minimum efficiency of the two processes, instead of the product of the efficiencies. Figure 2-4 shows the simple interaction effect of PL by CFO under loosely coupled processes.

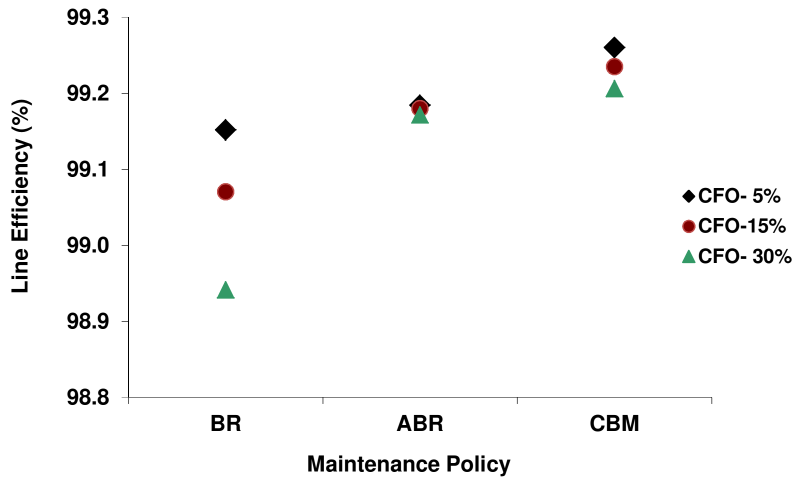

Figure 2-4: Policy – CFO simple interaction effect on line efficiency under loosely coupled processes

Under loosely coupled processes, CBM performs best with respect to line efficiency and BR worst. Furthermore, the chance of failure within PM intervals has a negative effect on the line efficiency. Finally, Figure 2-4 shows that CFO has a minimal effect on availability in ABR, a larger effect in CBM, and the largest effect in BR.

Under tightly coupled processes, blockage and starvation became 0.47%. This resulted in a decrease of LE compared to the loosely coupled processes and a different ranking of the policies. Block replacement turned out to be the most efficient policy (LE of 97.88%), then CBM (LE of 96.96%) and finally ABR (LE of 96.79%). In both production contexts, LE decreases when increasing CFO. This is obviously due to the fact that by increasing CFO, the number of unpredicted failure increases, which adversely affects the efficiency. However, the effect of CFO is larger under tightly coupled processes than under loosely coupled processes. For tightly coupled processes (see Figure 2-5), the difference in LE between a CFO of 5% and 30% is about 0.80% for BR, 0.17% for ABR and 0.21% for CBM. Moreover, pairwise comparisons of the simple simple main effects of PL using Sidak adjustments reveal that the differences in LE between ABR and CBM are statistically significant for all CFOs in the tightly coupled processes.

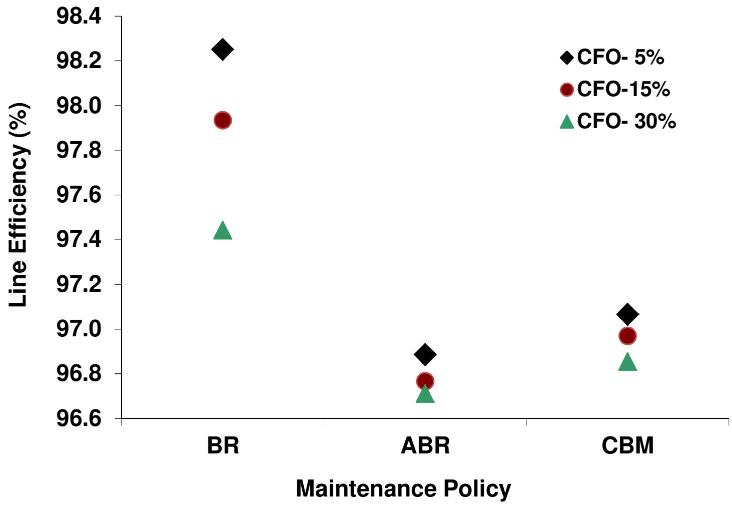

Figure 2-5: Policy – CFO simple interaction effect on line efficiency under tightly coupled processes

2.7 Summary & Conclusions

Condition-based maintenance is extensively appreciated in academia and there is a growing trend towards this maintenance policy in practice. At the same time, there is evidence that majority of CBM programmes fail or are not financially justifiable. In this chapter, we investigated one of the reasons for these failures. We conjectured that these failures are mostly rooted in using incomprehensive metrics for CBM programme justification. In particular, the metrics do not show CBM effectiveness in a plant-wide perspective.

We developed a simulation model to explore the effects of production context using traditional performance indicators (costs and system availability) and a more comprehensive metric (line efficiency).

The production context does not have an effect on the traditional performance indicators. In all scenarios, CBM results in the lowest total annual maintenance costs and the highest system availability. With these results one can easily justify CBM programmes. When the PM intervals are not optimal, there are higher chances of failure occurrence within the intervals. Therefore the number of corrective maintenance actions and subsequently total maintenance cost increases, while the system availability decreases. Under these circumstances, CBM performs quite better. In the model, the initial investment for CBM has not been considered. Therefore, adding this cost can negatively affect the choice for a CBM programme.

When line efficiency is considered, CBM still performs best under loosely coupled processes. However, under tightly coupled processes, justifying CBM becomes more difficult. Blocking and starvation have a negative effect on line efficiency and particularly for ABR and CBM. In this production context, BR performs best. Not taking into account the negative effects of blocking and starvation in the justification of a CBM programme will thus result in a too optimistic outcome and this possibly explains the large number of failures of CBM in practice.

CHAPTER 3

CBM in the context of opportunistic maintenance

In this chapter we will examine the impact of opportunistic maintenance on the effectiveness of CBM. We simulate a three-component system in series and vary the number of components under a CBM policy, the length of the opportunistic maintenance zone, the cost benefits of grouping maintenance activities, and the chance of a failure occurrence within a PM interval.

This chapter is based on the following manuscript:

"Koochaki, J., Bokhorst, J.A.C., Wortmann, J.C., & Klingenberg, W. 2011a. Condition based maintenance in the context of opportunistic maintenance. *International Journal of Production Research*, forthcoming".

3.1 Introduction

Maintenance policies for production systems serve two goals: one goal is to maximize plant availability and the other goal is to minimize costs. Selecting an appropriate maintenance policy has a significant impact on achieving these goals. An efficient maintenance policy enables companies to maximize their production and reduce the physical assets life cycle costs.

Condition Based Maintenance is a maintenance policy for equipment components, which is based on monitoring the operating condition of the component (Moubray 1997). When applicable, CBM allows just-in-time maintenance for the component, because maintenance can be done just before the component fails. CBM is a preventive maintenance policy in which the incipient faults can be identified before their occurrence. Eliminating sudden failures and performing maintenance as it is needed make this policy very attractive and may justify the initial investment and further use of this policy (Kelly 2006).

Several studies have been carried out on how to (technically) implement CBM (Jardine et al. 2006). However, few attempts have been made to analyze the effectiveness of CBM programmes. Moreover, the studies that have focused on the effectiveness of CBM mainly consider a single piece of equipment instead of a multi-component system (Koochaki et al. 2008, Li et al. 2009). This confirms the statement by Raheja et al. (2006) that the CBM programmes are not always in line with the holistic maintenance goals of the organization.

Opportunistic maintenance (Nicolai and Dekker, 2008) is not a maintenance policy for a single component, but for a collection of components in a production line or plant. Opportunistic maintenance aims to create efficiency for a maintenance crew, by combining various maintenance activities on different plant components. Although the goal of opportunistic maintenance is to reduce maintenance costs, it may also impact plant availability. If maintenance of a component implies plant shutdown, then plant availability may be better served by combining maintenance activities on several components.

There are various reasons to study the interaction of CBM and opportunistic maintenance. First, the theoretical advantages of CBM for plant components are not necessarily transferable to the plant level (Koochaki et al. 2008). This justifies a study at the level of the production line or plant. Furthermore, CBM may provide the right information to execute an opportunistic maintenance policy, because CBM provides a time zone in which maintenance activities can be combined: an opportunistic maintenance zone. This is the period of time during which degradation has started and therefore maintenance makes sense, but during which degradation does not yet lead to fatal shutdown of the component. Therefore, opportunistic maintenance could benefit from a well-implemented CBM policy. To the best of our knowledge, no papers have thoroughly studied CBM in an opportunistic maintenance context.

The next section provides an overview of CBM and of opportunistic maintenance models in particular. Section 3.3 poses the chapter question (RQ2) and addresses the research method used. Section 3.4 describes the model and introduces the fixed and experimental factors. The results are presented in section 3.5. Section 3.6 concludes the chapter.

3.2 Literature review

CBM effectiveness has been mostly framed as a problem of selecting the right maintenance policy for a single piece of equipment. For instance, Waeyenbergh & Pintelon (2002) have considered a wide range of factors and proposed a practical and comprehensive framework for selecting a maintenance policy. Najjar & Alsyouf (2003b) developed fuzzy logic principles to select the most efficient maintenance policy. Bertolini & Bevilacqua (2006) used a combination of Analytical Hierarchy Process (AHP) with goal programming for the selection problem, etc. (for an extended review, refer to (Jardine et al. 2006) and (Koochaki et al. 2008); for a mathematical formulation of the CBM problem, see Kolarik (1995). However, there is hardly any literature regarding plant-wide CBM evaluation because few studies consider multi-component systems (Li et al. 2009).

The focus of this study is on investigating the effectiveness of CBM in a multi-component system. The previous chapter (Koochaki et al. (2011b)) focused on the effectiveness of CBM on a system of two components in series, but they did not include opportunistic maintenance strategies. As argued in the introduction (section 3.1), there are good reasons to study the plant-wide use of CBM in combination with opportunistic maintenance strategies. Therefore, we focus our review on opportunistic maintenance models.

Nicolai & Dekker (2008) classified the multi-component systems based on the economic, structural and stochastic dependencies between the components. An economic dependency refers to the cost synergy due to performing group maintenance while stochastic and structural dependencies display the physical interaction between components. The concept of opportunistic maintenance is based on the economic dependency among the components (Rao & Bhadury 2000).

The simultaneous maintenance actions are performed by proceeding and/or postponing maintenance activities for individual components, which results in lower maintenance costs.

The opportunistic maintenance models can be roughly categorized into (n_i,N) opportunity-based age replacement and [L-u,L] hazard-rate tolerance methods (Nowakowski & Werbinska 2009).We will now discuss these two types.

The (n_i, N)-policy was firstly introduced by Radner & Jorgenson (1963). In their model, they assumed that one of the components in the system is uninspected while the others are monitored. The uninspected part is replaced in case of sudden failure or when it reaches to preventive maintenance age N. The uninspected component is opportunistically replaced in the time frame [n,N], if a monitored component fails. Later, this model was extended by several researchers. For instance, Van der Duyn Schouten & Vanneste (1990) investigated this policy for two components in series. Wang et al. (2001) applied imperfect maintenance concepts in this context.

Gertsbakh (1984) modeled a system of n identical components with control limit [t, T]. If a component fails within time [0,t], it will have individual corrective replacement. If it fails within time [t,T], the failed component will have corrective and the other components will have preventive replacement. If no failure occurs before T, the whole system is replaced.

Jhang & Sheu (1999) considered a system with minor and major failures. The component is minimally repaired when a minor failure happens and it is replaced as a major failure occurs. The system is replaced at a major failure or at the opportunity after age T, whichever occurs first. In this model, the repair time is not considered.

Kaspi & Shabtay (2003) defined an opportunistic and an integrated replacement strategy. In the opportunistic replacement strategy, all tools are replaced as one of the tools fails. In the integrated replacement strategy, when a failure occurs, the tools that are older than a certain age are replaced in addition to the failed tool.

Ritchken & Wilson (1990) used m and T control limits for their opportunistic model. The system replacement is carried out if the mth component failed or if the system reaches time T without m components failing. In this model, the failed components are kept idle if the above replacement rules are not met. Pham & Wang (2000) have studied opportunistic maintenance for k-out-of-N systems. In their model, minimal repairs are carried out if the failures occurred in [0, τ]. For the failures within [τ, T], the components are lying idle until the mth (m = n –k +1) component fails. If m components fail in the time interval [τ; T], CM is performed in combination with PM; if less than m components fail, PM is carried out at time T.

Although k-out-of-N systems can be viewed as a general configuration, they are mostly classified as a special case of parallel redundancy. Hence, this model is more suitable for parallel systems than in series. Further, the repair times for the minimal repairs have not been included in the model.

Zheng & Fard (1992) proposed a hazard-rate tolerance method for an opportunistic replacement policy. Components are replaced at failure or when their hazard (failure) rates exceed the limit L, whichever occurs first. When a component is replaced because its hazard rate reaches L, all the operating components with their hazard rate falling in the threshold limits (L-u, L) are replaced. In this model, for simplification, the mean time to repair is neglected and all components use the same maintenance policy. Levrat et al. (2008) applied 'odds algorithm' to find the optimal stoppages (which are already planned) for performing maintenance tasks. They used the residual lifetime of the component and product performance parameters. In the model, it was assumed that the production stoppages and their respective durations are independent random variables.

The literature review shows that most of the existing papers studied the application of opportunistic maintenance in combination with preventive maintenance policies other than CBM. Furthermore, the components in the models reviewed usually have the same type of maintenance policy. The existing models are usually analytical and do not consider repair and/or replacement times. Our research question will be discussed the next section.

3.3 Research question and method

In this chapter, we aim to answer the question:

Can CBM be effectively applied in multi-component systems using an opportunistic maintenance strategy?

We use simulation as research method. This is necessitated by the complexity of the analysis, which will include stochastic variables and interactions between system elements. We will analyze a multi-component system to which we will apply a combination of CBM and opportunistic maintenance. To study the effectiveness of CBM in an opportunistic maintenance context, we modeled a three-component system in series both in an opportunistic and in a non-opportunistic maintenance context. This configuration is typical in line manufacturing or in process industries. Our opportunistic maintenance rules are inspired by the models in Gertsbakh (1984) and Zheng & Fard (1992). We use dynamic grouping, in which group maintenance will be carried out only for the non-failed components that are in the opportunistic zone. The components either use CBM or Age Based Replacement (ABR) policies. The next section describes the model in detail.

The simulation model was developed using the discrete event simulation software tool Tecnomatix Plant Simulation (Siemens). The models were verified by comparing event occurrences with flow logic diagrams, tracing and debugging (Banks et al. 2009) and were validated in its simplest form through analytical techniques. Each experiment consisted of 40 runs that provided us with statistically reliable results. Accordingly, each run was carried out with different seeds to create maximum independence. Each run was simulated for 3650 days (10 years) after a warm up period of 730 days (2 years). The results were analyzed in PASW Statistics (SPSS) by means of several Analyses of Variance (ANOVAs).

3.4 Model description

In our study, we analyze a serial production system consisting of three components. There are no buffers in between the components, as commonly encountered in line production and in process industries. The inputs are transformed sequentially and leave the production line as finished output. The following assumptions were made in developing the model:

i. The input material is infinite (the first component never starves) and the components are fully utilized (100%) in the ideal scenario;

ii. Transport times from and to components are neglected;

iii. After any maintenance activity, the condition of the components will change to as-good-as-new;

iv. Implementing CBM is technically feasible for all components;

v. Under a CBM policy, the condition of the component is monitored continuously.

In the next sections, the simulation model is described by distinguishing the fixed and experimental factors and by introducing the performance indicators.

3.4.1 Fixed factors

The system operates continuously (24 hours a day seven days a week). In the case that preventive maintenance (PM) or corrective maintenance (CM) action is required, the production line stops for a fixed Mean Time To Repair (MTTR) of 24 hours. If opportunistic maintenance leads to grouping of maintenance activities, then the MTTR remains 24 hours. We assume that enough resources are available to maintain all grouped components in 24 hours.

The PM costs (C_{PM}) include man-hour expenditure, the spare parts shipping cost and other indirect cost due to performing maintenance activities. The failure occurrence is unpredicted and immediate action is required to restrict the amount of time lost due to sudden line stoppages. Therefore, higher costs are incurred for CM than for PM. We assumed corrective maintenance costs (C_{CM}) to be one-and-half times the PM costs (increasing this cost ratio yielded predictable results; we therefore did not include the cost ratio as an experimental factor). If maintenance activities are grouped, all individual maintenance costs are incurred (all C_{CM} and/or C_{PM} involved), but with a small cost reduction due to the economies of scale of performing collective maintenance activities. This will be further explained in the experimental factor 'percentage of positive economic dependency'.

The component failures occur according to a gamma distribution ($g(x;\alpha,\beta) = \frac{\beta^{\alpha}}{\Gamma(\alpha)} x^{\alpha-1} e^{-\beta x} \text{ for } x > 0$) in which α is the shape and β is the scale parameter. This distribution is widely used to model failure functions both in the literature as well as in successful maintenance applications in industry (Van Noortwijk 2009). We have set the mean of the failure function (MTBF) at 72 days.

The components in our model follow either a CBM or an ABR policy. CBM is carried out based on the results of condition monitoring techniques. We assume that any failure that will happen under this policy is noticed earlier and treated as a scheduled maintenance activity with PM costs. Hence, CBM is ideal in our model since there will be no CM for any component under a CBM policy. This assumption is valid if a link can be established between the operating conditions and the maintenance planning (Selim & Gurel 2007).

We specifically compare CBM to ABR since ABR is widely used in practice and more efficient than other preventive maintenance approaches (e.g. block replacement). In ABR, components are replaced after a fixed time interval (using PM) or at the occurrence of a failure (using CM), whichever occurs first. Any unpredicted failure postpones the next PM activity. Thus, the interval starts after any maintenance activity (i.e. PM or CM) and ends either with a failure or with a PM activity. In our simulation, the PM interval is 60 days after the previous maintenance activity has finished.

3.4.2 Experimental factors

We investigated four experimental factors in our model:

i. The number of components under a CBM policy;

ii. The length of the opportunistic maintenance zone;

iii. The percentage of positive economic dependency;

iv. The chance of a failure occurrence within a PM interval.

The first factor is the main factor that gives insight into the effects of (partially) implementing CBM in a production line. The second and third factors are included to show whether the length of the opportunistic maintenance zone or the percentage of positive economic dependency affect CBM effectiveness in exploiting opportunistic maintenance. Finally, the fourth factor indicates the sensitivity of the relation between the failure distribution and the PM interval. Insight into this relation enables us to compare CBM with ABR policies more precisely.

In addition to the experimental factors mentioned above, two new factors are introduced, experimented with and analyzed in section 5.3. This extends the research of the paper this chapter is based on.

3.4.2.1 Number of components under a CBM policy

In our model, we define four scenarios based on the maintenance policies chosen for each of the three components. These scenarios are designed based on the number of components under a CBM policy in the system (see Figure 3-1). Since the components have identical processing and failure characteristics and there are no buffers in-between the components, the position of components with CBM in the group does not have any effect on the results. This was verified in experiments with our model.

0	ABR → ABR → ABR
1	CBM → ABR → ABR
2	CBM → CBM → ABR
3	CBM → CBM → CBM

Figure 3-1: Number of components under a CBM policy.

3.4.2.2 Length of the opportunistic maintenance zone

Opportunistic maintenance has generally been developed and modeled for preventive maintenance policies like ABR. Only a few papers, e.g. Zheng & Fard (1992) used the condition of the equipment (hazard rate) in their opportunistic maintenance strategy. In our system, components use either ABR or CBM. Therefore, we defined a new set of opportunistic maintenance rules that are applicable and logical for both policies and / or a combination of these policies.

We used a dynamic grouping concept in the modeling of our opportunistic maintenance strategy. At the start of a CM or PM maintenance activity for a specific component, all other components are checked. The components that are in the opportunistic maintenance zone will undergo PM as well, in a combined group maintenance activity. Instead of having separate maintenance activities for each component (which may (partially) overlap or not), a single group maintenance activity is scheduled. If a component is breaking down when a maintenance activity is being performed on another component, we consider the necessary CM as a separate maintenance activity, even though the activities do overlap. We defined the opportunistic maintenance zone in ABR as a percentage of the PM interval T (see Figure 3-2).

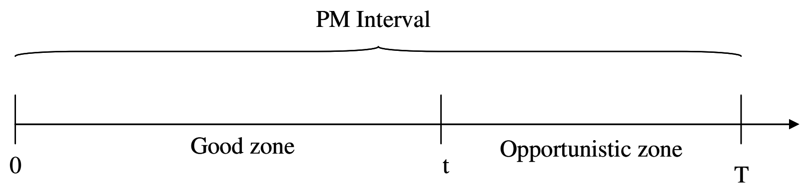

Figure 3-2: Opportunistic maintenance zone in PM policy.

In CBM, we defined the opportunistic zone to be (part of) the "P-F interval". The P-F interval is a part of the degradation curve. It starts at a point where a potential failure can be detected (P) and ends at a point when the failure occurs (F) (Moubray 1997). We assume that any failure that will happen is noticed and treated as a scheduled maintenance activity at point F (see Figure 3-3). In case of opportunistic maintenance, the maintenance activities can start at an arbitrary point within the opportunistic zone (which is equal to or smaller than the P-F interval). This opportunistic zone is the period of time during which degradation has started, without it leading to a fatal shutdown of the component. Within the opportunistic zone, PM activities can be performed against PM costs.

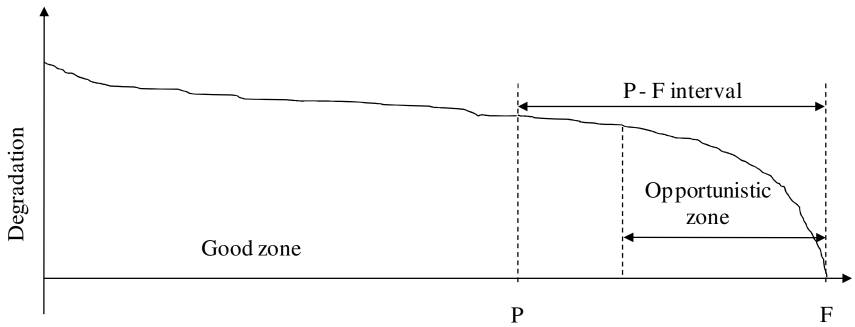

Figure 3-3: Opportunistic maintenance zone in CBM policy.

The length of the opportunistic maintenance zone probably has an effect on the number of group maintenance activities. A larger zone increases the number of group maintenance activities (which decreases the number of individual maintenance activities), but it may also increase the total number of maintenance activities since components are on average maintained sooner than without opportunistic maintenance. We varied the length of the opportunistic maintenance zone in our experiments using three scenarios: (1) no opportunistic maintenance zone, (2) a "small" opportunistic maintenance zone, and (3) a "large" opportunistic maintenance zone. For ABR, this means 0%, 10%, and 20% of the PM interval and for CBM, it means 0 days, 6 days and 12 days before degradation reaches its critical point (i.e. point F, which is the last moment a PM activity can be performed).

3.4.2.3 Percentage of positive economic dependency

Cost reduction is one of the main motivations for companies to perform group maintenance. In this perspective, performing a joint maintenance activity is cheaper than performing individual maintenance activities. According to Nicolai & Dekker (2008), this notion is called "positive economic dependency" and it occurs due to the economies of scale of performing collective maintenance activities.

The percentage of economic dependency affects the total maintenance costs. The economic gain (EG) is determined by means of equation 3-1. Here, N is the number of group maintenance activities, PED is the percentage of positive economic dependency, and C_{PM} is the PM cost. The economic gain is thus a fixed cost reduction (expressed as a percentage of PM costs) for each group maintenance activity. The number of group maintenance activities depends on factors such as the length of the opportunistic maintenance zone of the components. For PED we experimented with scenarios of 10% and 20%.

$$EG = N * PED * C_{PM} \qquad (3\text{-}1)$$

3.4.2.4 Chance of failure occurrence within PM intervals

Finding an optimum maintenance interval is one of the most challenging tasks in implementing ABR. Short intervals increase preventive maintenance costs, while long intervals boost the chance of failure occurrence and subsequently increase corrective maintenance costs. To compare CBM with ABR, it is important to be aware of the optimality of the PM intervals and the chance of failure within those periods.

To address the above issue, we defined our failure function in such a way that there is a 10% probability of a failure occurring within the PM interval. This reflects the first scenario for this experimental factor. Then the mean of the function is kept and we adjusted the failure function parameters in such a way that the chance of failure within the PM interval increases to 20% (the second scenario). Note that this factor will affect components under an ABR policy, since it will change the ratio of CM versus PM activities for those components, but it will not affect components under a CBM policy.

An overview of all experimental factors with their corresponding scenarios is presented in Table 3-1:

Table 3-1: Overview of experimental factors and scenarios

N-CBM Number of components under a CBM policy	0	1	2	3

LOZ Length of opportunistic maintenance zone	zero	small	large

PED Percentage of positive economic dependency	10%	20%

CF-PM *Chance of failure occurrence within pm intervals*	10%	20%

3.4.3 Performance indicators

Line productivity and total maintenance costs are used as the performance indicators in this study. These or similar indicators are widely used to measure maintenance performance both in industry and academia (Lofsten 2000).

3.4.3.1 Line productivity (%)

Line productivity (LP) is used to indicate the effectiveness of a maintenance policy. It denotes the percentage of time that the line is productive. In the simulation, the components process small jobs with a processing time of 1 minute to represent continuous production. The line productivity is calculated by equation 3-2:

$$\text{Line productivity} = \frac{100 * \text{processing time of a job} * \text{output of the line in number of jobs}}{\text{simulation time in minutes}} \qquad (3\text{-}2)$$

In our serial production system without buffers, the line is not productive during a maintenance activity (either CM or PM). Components that are not involved in the maintenance activity are blocked or starved during the maintenance activity and are thus forced down. Line productivity is improved when the total number of maintenance activities is decreased.

3.4.3.2 Total maintenance costs

Total maintenance costs are the sum of the annual CM and PM costs minus the economic gain obtained because of the positive economic dependency when components received maintenance services in a group maintenance activity. Total maintenance costs are expressed in PM costs (x * C_{PM}) and are calculated through equation 3-3:

$$\text{Total maintenance costs} = \begin{pmatrix} \text{\# PM activities} + 1.5 * \text{\# CM activities} \\ \text{- \# group maintenance activities} * \text{PED} \end{pmatrix} * C_{PM} \qquad (3\text{-}3)$$

Note that the PM and CM activities performed as a grouped maintenance activity are also counted separately in the cost equation. For example, if a CM activity of component 1 is grouped with a PM activity of component 2 and PED equals 10%, the maintenance costs are (1 + 1.5*1 – 1*0.1)* C_{PM} = 2.4* C_{PM}. In our cost calculation, product quality issues such as startup losses, defects or rework costs are not included. Further, since the initial investment of a CBM programme has merely a predictable offsetting effect on the total maintenance costs, it is not included in the calculation.

3.5 Results

Forty-eight experiments (four N-CBM x three LOZ x two PED x two CF-PM) were performed to investigate the effects of (partially) applying CBM in an opportunistic as well as in a non-opportunistic context.

In the analyses for line productivity, we have excluded the independent variable PED. PED only has an effect on costs and not on line productivity, since this financial factor does not influence the number of maintenance activities that need to be performed. We used Analysis of Variance (ANOVA) to analyze the effects of the number of components under a CBM policy, the length of the opportunistic maintenance zone and the chance of a failure occurrence within a PM interval as independent variables and line productivity as dependent variable.

In addition, we used a separate ANOVA to analyze the effects of the number of components under a CBM policy, the length of the opportunistic maintenance zone, the percentage of positive economic dependency, and the chance of a failure occurrence within a PM interval as independent variables and total maintenance costs as dependent variable. Where necessary, post hoc tests (i.e. Tukey’s range tests) were carried out as a follow up. The analyses of the results for line productivity are discussed in section 3.5.1 and for total maintenance costs in section 3.5.2.

3.5.1 Line productivity

Table 3-2 shows the ANOVA results for line productivity (LP) as a dependent variable.

Table 3-2: ANOVA results for line productivity

Source	*Line productivity*	
	F	*p- value*
N-CBM	112.1	<0.001
LOZ	5078.2	<0 .001
CF-PM	436.6	<0.001
N-CBM * LOZ	225.6	<0.001
N-CBM * CF-PM	163.8	<0.001
LOZ * CF-PM	52.7	<0.001
N-CBM * LOZ * CF-PM	19.9	<0.001

All main effects and interaction effects are significant. This chapter focuses on the questions what the effect is of implementing CBM in a multi-component system and whether CBM can effectively exploit opportunistic maintenance strategies in such systems. Therefore, we will analyze the results by describing the interactions that include N-CBM and LOZ.

Figure 3-4 shows that without opportunistic maintenance (LOZ = 0), LP increases when more components use CBM (i.e. when N-CBM is increased). This can be explained by the fact that the number of maintenance events decreases when more components use CBM. Under ABR, the maximum time between maintenance events is set at 60 days (the fixed time interval). Under CBM, components will be repaired at the time the failure is about to happen, which means that the average time between maintenance events is 72 days. Therefore, by implementing CBM, less time is spent on maintenance activities, which increases uptime and line productivity.

With opportunistic maintenance, maintenance events for components are more synchronized and the percentage of group maintenance activities increases. Even though the number of maintenance events for individual components increases, the total number of maintenance events for the system decreases. This positively affects LP, as shown in Figure 3-4. If the opportunistic maintenance zone (LOZ) is increased, more opportunistic maintenance is performed, which improves LP. This effect is largest if all components use ABR. For instance, under low CF-PM (i.e. 10%), the number of maintenance events in an all ABR system is reduced by 38% when moving from a non-opportunistic system (LOZ= zero) to a small opportunistic zone (LOZ= small) and by another 24% when moving from a small opportunistic zone to a large opportunistic zone (LOZ=large). Over all experiments, the highest LP (98.1%) is achieved for the system with all machines using ABR under large LOZ.

Increasing the number of components using CBM decreases the effect of applying opportunistic maintenance. This effect can be explained by the fact that components using ABR have more scheduled maintenance activities (because of the maximum time interval of 60 days) than components using CBM. The chance that single maintenance activities can be grouped then increases, which prevents blocking and starving in the system and increases LP. With respect to LP, CBM thus seems less effective in making use of opportunistic maintenance than ABR.

By increasing CF-PM, the number of unpredicted failures increases for components with an ABR policy, which adversely affects LP for systems with at least one component under ABR. This negative effect is thus largest when all components use ABR and it is not present when all components use CBM.

In order to improve LP in this multi-component system, it appears to be more effective to implement opportunistic maintenance strategies in a system with all components or two components under ABR than to try to increase the number of components under CBM.

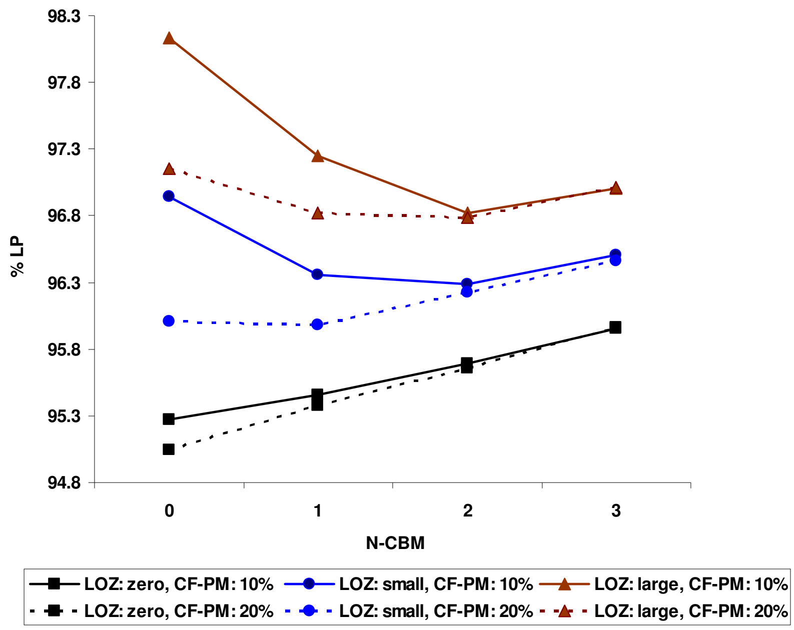

Figure 3-4: The interaction effect of N-CBM, LOZ and CF-PM on the line productivity.

3.5.2 Total maintenance costs

Table 3-3 shows the ANOVA results for number of components under a CBM policy, length of opportunistic maintenance zone, percentage of positive economic dependency and chance of a failure occurrence within a PM interval as independent variables and total maintenance costs as dependent variable.

Table 3-3: ANOVA results of significant effects on total maintenance costs

Source	***Total maintenance costs***	
	F	***p- value***
N-CBM	14042.5	<0.001
LOZ	701.3	<0.001
CF-PM	2613.4	<0.001
PED	498.8	<0.001
N-CBM * LOZ	101.1	<0.001
N-CBM * CF-PM	559.3	<0.001
N-CBM * PED	19.3	<0.001
LOZ * CF-PM	40.9	<0.001
LOZ * PED	161.8	<0.001
CF-PM * PED	6.7	0.010
N-CBM * LOZ * CF-PM	9.4	<0.001
N-CBM * LOZ * PED	5.9	<0.001
N-CBM * CF-PM * PED	2.8	0.040

We will once more analyze the results by describing the interactions that include N-CBM and LOZ. Figure 3-5 shows the interaction effect of N-CBM and LOZ for 10% and 20% CF-PM. For all levels of LOZ, increasing N-CBM reduces the total maintenance costs. The system has the lowest annual maintenance costs (around 14.7* C_{PM}) when all components use CBM with either small or large LOZ. The highest annual costs (20.11* C_{PM}) occur in a system where all components use ABR, with zero LOZ and 20% CF-PM.

Figure 3-5 also shows that opportunistic maintenance decreases total maintenance costs for all levels of N-CBM, while the effect is largest when all components use ABR and smallest when all components use CBM. Applying opportunistic maintenance results in shorter PM intervals, more group maintenance events and a decreased total number of maintenance events. This decreases the annual maintenance costs. It also decreases the number of (more costly) corrective maintenance events for components using ABR, explaining the larger effects when all components use ABR compared to when all components use CBM.

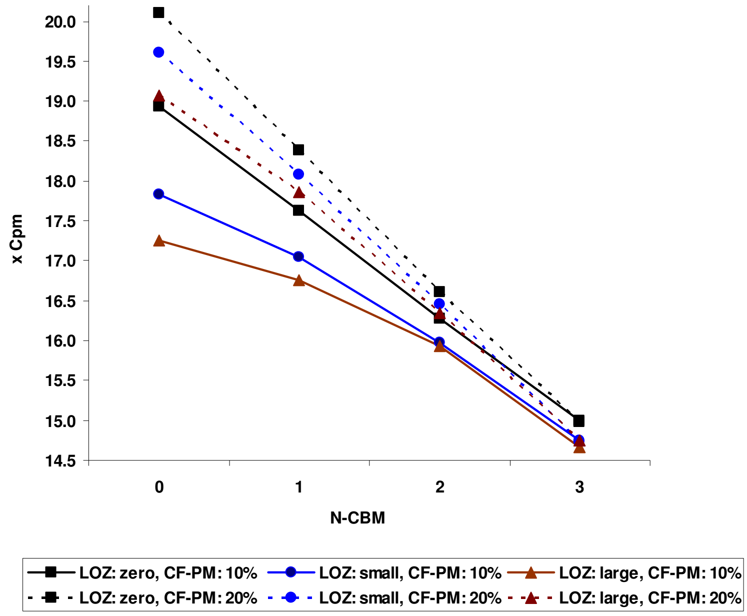

Figure 3-5: The interaction effect of N-CBM, LOZ and CF-PM on the annual maintenance costs.

As expected, PED significantly affects total maintenance costs in systems with opportunistic maintenance (i.e. small or large LOZ), see Figure 3-6. The higher the positive economic dependency, the lower the maintenance costs. The effect of PED is larger in an all ABR system than in an all CBM system, since the effect of group maintenance is larger in systems with more components under ABR.

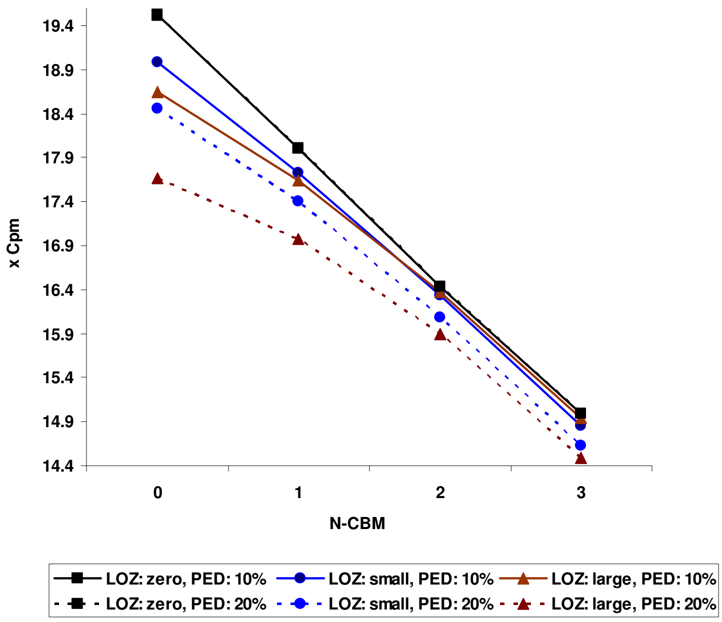

Figure 3-6: The interaction effect of N-CBM, LOZ and PED on the annual maintenance costs.

3.6 Conclusions

In this chapter, we have studied whether CBM can be effectively applied in multi-component systems in an opportunistic maintenance context. We built a simulation model of a small system consisting of three components in series and experimented with the number of components under a CBM policy, the length of the opportunistic maintenance zone, the percentage of positive economic dependency, and the chance of a failure occurrence within a PM interval.

The results show that there is no single optimum maintenance policy in a multi-component system when both performance measures are considered. In our experimental settings, implementing CBM for all three components combined with an opportunistic maintenance strategy would minimize maintenance costs, but would not maximize line productivity. In contrast, three components under ABR combined with an opportunistic maintenance strategy would maximize line productivity, especially if the chance of a failure occurring within the PM interval (CF-PM) is low, but it would not minimize costs.

Opportunistic maintenance synchronizes maintenance activities, which is found to improve line productivity and decrease the annual maintenance costs in a serial configuration. Since less maintenance activities can be grouped using CBM than using ABR, CBM is less effective in making use of the beneficial effects of group maintenance than ABR. With opportunistic maintenance, ABR may perform better than CBM with respect to line productivity. With respect to annual maintenance costs, CBM remains most cost effective.

In deciding which maintenance policy to use in practice, several issues play a role. Our results already show that there may be a trade-off between annual maintenance costs and line productivity. Implementing CBM for all components minimizes maintenance costs, but some line productivity may be sacrificed. A larger LOZ could improve line productivity in this situation, but whether this is possible depends on the length of the P-F interval of the specific equipment used. Other practical considerations are whether it is technically feasible to implement CBM and at what (initial and/or inspection) costs (Golmakani & Fattahipour 2010), the accuracy of the PM interval that is chosen for equipment under ABR (related to CF-PM), the extent of the cost reduction that can be obtained with group maintenance (related to PED) and the ratio between corrective and preventive maintenance costs. When the cost ratio increases, preventing corrective maintenance will become more important compared to aiming for the maximum line productivity. CBM will then always be preferred because of the lower annual maintenance costs, even when some line productivity losses have to be incurred.

CHAPTER 4

Impact of maintenance workforce capacity on CBM benefits

In Chapter 4, we will study the impact of using CBM in serial and parallel multi-component systems with different types of maintenance resources and their associated limitations. We will simulate a system consisting of three components for three situations: (1) a situation without worker constraints, (2) a situation with a single internal maintenance worker, and (3) a situation with external maintenance workers with a significant response time.

This chapter is based on the following manuscript:

Koochaki, J., Bokhorst, J.A.C., Wortmann, J.C., & Klingenberg, W. 2012. The influence of Condition Based Maintenance on workforce planning and maintenance scheduling. *International Journal of Production Research*, (under review).

4.1 Introduction

It has become clear that Condition Based Maintenance can have significant advantages over other types of maintenance (Mobley 2002, Veldman et al. 2011a, Veldman et al. 2011b). CBM is a maintenance policy for equipment components, which is based on monitoring the operating condition of the component (Moubray 1997). When applicable, CBM allows just-in-time maintenance for the component, because maintenance can be done just before the component fails. This also introduces a potential disadvantage: just-in-time maintenance means that grouping of maintenance activities may be troublesome, since the timing of the maintenance activities is primarily dictated by the deterioration of the operating condition of the components. However, CBM has so far been described in the literature from the viewpoint of a single component, which may be the reason why this disadvantage has not been explored yet in the literature. We have therefore investigated the effectiveness of CBM in multi-component systems and presented them the findings in previous chapters (Koochaki et al. 2011a, Koochaki et al. 2011b). In this chapter, we focus on the influence of CBM on efficient scheduling of the maintenance workforce, which, to the best of our knowledge, has not received any attention in the literature yet.

4.1.1 Maintenance workforce

Timely presence of maintenance resources is necessary for maximizing plant availability, which is typically one of the two goals of a maintenance policy. The other goal is to minimize costs, usually resulting in a continuous desire to minimize the number of personnel, including maintenance resources. Striking a balance between these two conflicting goals is one of the key challenges when designing a maintenance policy. Another challenge is that maintenance resources are usually highly skilled and therefore difficult to recruit. These challenges render the efficient and effective use of the scarce maintenance resources very important. This was recognized by other researchers, who have created important insights in this area using analytical modeling, optimization and simulation studies (Ahire et al. 2000, Ait-Kadi et al. 2011, Almeida 2005, Ben Ali et al. 2011, Bertolini et al. 2004, Langer et al. 2010, Martorell et al. 2010, Munoz & Villalobos 2002, Najid et al. 2011, Prosser et al. 1992, Safaei et al. 2008, Suryadi & Papageorgiou 2004). However, these papers mainly focus on resource allocation and scheduling problems given a particular maintenance policy to determine e.g. the optimum size of the maintenance workforce and the optimum maintenance schedule. In this chapter, we consider a multi-component system and focus on the influence of the choice for a particular type of maintenance policy on the efficiency and cost of maintenance scheduling and workforce planning. We will take into account the possibility of employing external maintenance workers, who may have a response time before start of work. Employing external maintenance workers is a well-established practice in maintenance (Veldman 2011).

More in particular, we will compare Condition Based Maintenance and Age Based Replacement in the context of opportunistic maintenance, whereby maintenance may or may not be ‘ideal’. We specifically compare CBM to ABR since ABR is widely used in practice and more efficient than other preventive maintenance approaches (e.g. block replacement). In ABR, components are replaced after a fixed time interval or at the occurrence of a failure, whichever occurs first (Marquez 2007). Any unpredicted failure postpones the next scheduled maintenance activity. The concepts of opportunistic maintenance and ideal (and non-ideal) failure prevention policy are explained in the next sections.

4.1.2 Opportunistic maintenance

Creating efficiency for a maintenance crew by grouping various maintenance activities on different components is the aim of opportunistic maintenance (Nicolai & Dekker 2008). Opportunistic maintenance is therefore not a maintenance policy for a single component, but for a collection of components in a production line or plant. Although the goal of opportunistic maintenance is to reduce maintenance costs, it may also impact plant availability. For example, if maintenance of a component implies plant shutdown, then plant availability may be better served by combining maintenance activities on several components.

4.1.3 Serial and parallel configurations

In serial configurations, if any one of the components fails, the entire system will come to a stop. By contrast, as long as not all of the components of a parallel configuration fail, at least part of the entire system functions.

Blocking and starving effects will negatively influence the performance of the serial configuration. Choosing a maintenance policy that will decrease blocking and starving is thus important in the serial configuration. Grouping of maintenance events will also decrease blocking and starving effects in the serial configuration (in the case there is enough labor capacity) and we expect ABR to perform better than CBM in grouping maintenance events.

4.1.4 Ideal and non-ideal failure prevention policy

Ideal failure prevention policy simply means that the maintenance activities do prevent all failures. Consequently, corrective maintenance (CM) is not required and only preventive maintenance (PM) suffices. Non-ideal CBM means that even though the operating condition of the component is monitored, some failures still occur unexpectedly and that therefore also corrective maintenance is required (Zio 2009). In practice it may amount to incorrect diagnoses or prognoses of failures due to human, software or hardware errors the CBM application. Non-ideal ABR means that unexpected failures may occur within the scheduled replacement interval, which will lead to corrective maintenance. A further comparison of ideal and non-ideal failure prevention polices is summarized in Table 4-1.

Table 4-1: Comparison of various maintenance policies

Maintenance policies	**Planning perspective**	**Type of failure prevention**	
		Ideal	Non-ideal
CM	short-term plan	N/A	
ABR	long-term plan	Always PM	Some CM within scheduled replacement intervals
CBM	medium-term plan	Always PM	Some CM due to inaccurate prognosis

If ABR is non-ideal, the corrective actions will disturb the smoothness of the maintenance plans and reduce the possibilities for grouping maintenance activities, because (the potential for) grouping can no longer be 'engineered' and planned long in advance, but becomes dependent upon the (unpredictable) timing of the failures. Also, CBM is of a more reactive nature than ABR, since it cannot be planned far in advance (Koochaki et al. 2011a, Koochaki et al. 2011b). It is expected that the reactive nature of the maintenance activities becomes even stronger if CBM is non-ideal. This may affect the possibilities for grouping of maintenance activities.

In previous chapters, we found that CBM remains cost effective in the multi-component serial system, because of the longer time between maintenance activities, but is less effective than ABR in grouping maintenance activities. In this chapter we will extend these findings by conducting a simulation and analysis of the influence of maintenance policies on workforce planning and maintenance scheduling. We modeled a three-component system into a serial and parallel configuration. We designed experiments for three types of maintenance resources: i) No maintenance worker constraints, ii) External maintenance workers with a response time, and iii) A limited number of internal maintenance workers. We also applied opportunistic maintenance. This strategy may improve the occupational rate of maintenance resources when there are resource availability constraints (Ait-Kadi et al. 2011)

The remainder of this chapter is organized as follows. In Section 4.3, the model is described, failure and maintenance characteristics are explained and the performance indicators are introduced. The simulation details and experimental design are described in Section 4.4. In Section 4.5, the simulation results are presented and discussed. Finally, the managerial implication of the results and concluding remarks are in Section 4.6.

4.2 Model description

We analyze production systems consisting of three components with identical characteristics. We model these components into a serial and a parallel configuration. The serial configuration transforms inputs sequentially, without buffers between the components. In the parallel configuration, the components transform inputs individually and independently. The system operates continuously (24 hours a day seven days a week). The following assumptions have been considered in developing the model:

i. The inputs are infinite (a first component never starves);

ii. Transport times to and from components are neglected;

iii. After any maintenance activity, the condition of the components will change to as-good-as-new;

iv. Implementing CBM is technically feasible for all components;

v. Under a CBM policy, the condition of the component is monitored continuously.

4.2.1 Failure and maintenance characteristics

In our experiments, we consider both ideal and non-ideal failure prevention policies: ideal failure prevention policy with only PM activities and non-ideal failure prevention policy with PM and CM activities. The Mean Time To Repair (MTTR) of each maintenance activity (PM, CM, or grouped) is fixed at 24 hours. Failures are generated by a gamma distribution with a mean of 72 days.

The components follow either a CBM or an ABR policy. In ABR, components are replaced after a fixed time interval or at the failure occurrence, whichever happens first. After the maintenance activity, the model determines the next time of failure according the gamma failure distribution. We assigned a 60-day PM interval for ABR. The gamma failure distribution is set in such a way that this results in a 10% chance of failure within the PM interval. In ideal ABR, the model ignores the failures happening within the PM intervals of ABR.

CBM is carried out based on the results of condition monitoring techniques. In ideal CBM, we assume that any failure that is generated by the gamma failure distribution is noticed earlier and treated at the time of failure as a scheduled maintenance activity with PM costs. The timing of the failure is shown as point ‘F’ in the P-F interval

(Moubray 1997). The P-F interval is a part of the degradation curve. It starts at a point where a potential failure can be detected (P) and ends at a point when the failure occurs (F). The P-F interval in the model is set at 15 days. In non-ideal CBM, an inaccurate failure prognosis can cause CM activities. For failures in CBM, the model assigns a CM activity instead of a PM activity in 10% of the cases. This CM is then scheduled randomly within the P-F interval.

The PM costs (C_{PM}) include man-hour expenditure, the spare parts shipping costs, and other indirect costs due to performing maintenance activities. The failure occurrence is unpredicted and immediate action is required to restrict the amount of time lost. Therefore, higher costs are incurred for CM than for PM. We assumed corrective maintenance costs (C_{CM}) to be one-and-half times the PM costs.

To make the model more realistic and show the multi-component environment effects, we included the concept of opportunistic maintenance to create efficiency for a maintenance crew by combining various maintenance activities on several components. Like previous chapter, we used a dynamic grouping concept in the modeling of our opportunistic maintenance strategy (Koochaki et al. 2011a). At the start of a CM or PM maintenance activity for a specific component, all other components are checked. The components that are in the opportunistic maintenance zone will undergo PM as well, in a combined group maintenance activity. Instead of having separate maintenance activities for each component, which may (partially) overlap or not, a single group maintenance activity is scheduled. If a component breaks down when a maintenance activity is performed on another component, we consider the required CM as a separate maintenance activity, even though the activities do overlap. We assume that the opportunistic maintenance zone in ABR is 10% of the PM interval, which is 6 days. In CBM, it is 6 days before the degradation reaches to a critical point (i.e. 6 days before the F point in P-F interval). In case of opportunistic maintenance in CBM, the maintenance activities can start at an arbitrary point within the opportunistic zone (which is smaller than the P-F interval).

Economic gain (EG), which is also called positive economic dependency (Nicolai & Dekker 2008), is one of the main motivations of companies to perform group maintenance activities. This gain occurs due to the economies of scale of performing collective maintenance activities. In our model, the economic gain is determined by means of equation (4.1). Here, N is the number of group maintenance activities, C_{PM} is the PM cost and 0.1 represents the positive economic dependency between components. The EG is thus a fixed cost reduction (here 10% of the costs associated to a single PM activity) for each group maintenance activity. Note again that the MTTR remains 24 hours.

$$EG = N * 0.1 * C_{PM} \tag{4.1}$$

4.2.2 Performance indicators

We used primary and secondary performance indicators to analyze the results. ‘Efficiency’, ‘total maintenance cost’ and ‘maintenance schedule’ are our three primary indicators which are used for all experiments. We also use ‘average group size’ and ‘maintenance delay’ as our secondary indictors in order to be able to explain some of the results better. The performance of serial and parallel configurations only differs with respect to efficiency, due to blocking and starving differences. Therefore, in the remainder of this chapter, we only present the distinction between the configurations for the performance indicator ‘efficiency’. All performance indicators are explained in more detail in the next sections.

4.2.2.1 Efficiency (%)

In our study, efficiency indicates the effectiveness of a maintenance policy. Based on the equipment’s configuration, we calculated this measure differently.

In the serial configuration, it represents the percentage of the system’s uptime periods. In this configuration, a component either is down for its direct maintenance activities or forced down due to blocking or starving during the maintenance activities of other components.

In the parallel configuration, the component is down only during its required maintenance activities and failures of the other components do not have any effect on the component’s uptime. Hence, we calculate efficiency as the average uptime of each component.

4.2.2.2 Total maintenance costs (TC)

Total maintenance costs are the sum of the annual CM and PM costs minus the economic gain obtained because of the positive economic dependency when components received maintenance services in a group maintenance activity. Total maintenance costs are expressed in PM costs (x * C_{PM}) and are calculated through equation 4.2:

$$\text{TC} = \begin{pmatrix} \text{\#PM activities + 1.5*\#CM activities} \\ \text{- \# group maintenance activities*0.1} \end{pmatrix} {*}C_{PM} \qquad (4.2)$$

Note that the PM and CM activities performed as a grouped maintenance activity are also counted separately in the cost equation. For example, if a CM activity of component 1 is grouped with a PM activity of component 2, the maintenance costs are (1 + 1.5*1 – 1*0.1)* C_{PM} = 2.4* C_{PM}. In our cost calculation, product quality issues such as start-up losses, defects or rework costs are not included. Further, since the initial investment of a CBM programme merely has a predictable offsetting effect on the total maintenance costs, it is not included in the calculation. Finally, as noted above, our way of modeling implies that there is no cost difference between serial and parallel configurations.

4.2.2.3 Maintenance schedule graph

As mentioned in the introduction (section 4.2), maintenance policies may adversely affect the smoothness of the maintenance plans. To illustrate this phenomenon, we use a maintenance schedule graph. The x-axis of the graphs represents a fixed time period. The data used for the maintenance schedule graphs are obtained from the simulation experiments (i.e. from the first simulation run of each experiment, where data is collected for a fixed time period after the warm-up period). Maintenance activities for each component are represented by a square in the graph. The left side of the square relates to the timeline and represents the beginning of the maintenance activity. Figure 4-1 is an example of a maintenance schedule graph. It shows that the first maintenance activities of component two and component three are grouped, whereas the first maintenance activity of component one is performed later in time and as a single activity. Also, it shows that the time between maintenance activities is not fixed and that the grouping of maintenance activities is not standard.

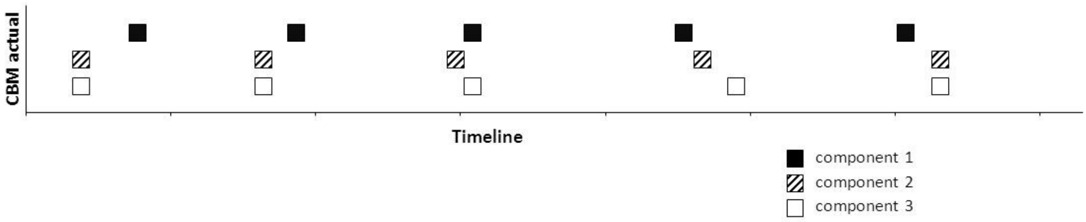

Figure 4-1: Typical maintenance schedule graph

4.2.2.4 Average group size

The average group size indicates the average number of components that is repaired during a single maintenance activity. When the average is close to 1, there is not much grouping of maintenance activities and when the average is close to 3, almost all maintenance activities are grouped.

4.2.2.5 Average maintenance delay

In some experiments, maintenance activities are outsourced and there is a delay between the request for a maintenance activity and the start of the actual activity. Preventive maintenance can be planned beforehand and therefore these activities will be done at their scheduled times. However, in the case of a sudden failure, there will be a delay between failure and the start of the CM activity. In this case, the component sits idle until the maintenance workers are available. The average maintenance delay indicates the average time a component has to wait for the availability of maintenance workers when a sudden failure occurs.

4.3 Design of experiments

We designed and carried out experiments with three types of maintenance resources that differ based on the availability and type of maintenance workers: (1) no maintenance worker constraints, (2) external maintenance workers with a response time, (3) a limited number of internal maintenance workers. All experiments were performed for the serial as well as the parallel configuration.

The experiments without worker constraints simplify reality most, since practical situations probably always have to take the availability of maintenance workers into account. In these experiments, we also compare ideal and non-ideal failure prevention policies. The results of these experiments without worker constraints are for the most part quite predictable and used to verify the model.

The experiments that model either external or internal maintenance workers are more realistic and only include non-ideal failure prevention policy. When using external maintenance workers, a response time is included for the maintenance workers to answer a call for CM activities. This demonstrates the effect of outsourcing maintenance activities. When using an internal maintenance workforce, we modeled a limited number of maintenance workers. This reveals the advantages and disadvantages of in-house maintenance crews with a limited number of workers.

Each experiment consists of 40 runs that provide us with statistically reliable results. Accordingly, each run was carried out with different seeds to create maximum independence. Each run was simulated for 3650 days after a warm up period of 730 days.

4.3.1 No maintenance worker constraints

Ideal vs. non-ideal failure prevention policy and the type of maintenance policy (ABR vs. CBM) are used as experimental factors, resulting in four experiments per configuration (serial and parallel). For these experiments, we assume that at any time enough maintenance workers are available. Maintenance actions are thus performed immediately upon request. Most papers on maintenance policies (Al-Najjar & Alsyouf 2003b, Waeyenbergh & Pintelon 2002) use this assumption and so do not impose any resource constraints. Since grouping of maintenance activities can be very beneficial in ideal failure prevention policy without resource constraints, we scheduled the very first maintenance activity of all the three components at the same time.

4.3.2 External maintenance workers with a response time

Here the experimental factors are the type of maintenance policy (ABR vs. CBM) and response time (2, 6, 10, and 14 days), resulting in eight experiments per configuration. For these experiments, we assume that the maintenance activities are outsourced and that the resources are available for CM after a response time. This assumption is quite common in practice. The duration of the response time is often negotiable to some extent, which is reflected in the contract price negotiation. The PM activities are planned beforehand and are thus not affected by the response time.

We assume that at any maintenance activity, a sufficient number of workers are available to perform group maintenance for other components (if it is required). Furthermore, we assume that the maintenance of a randomly failed component can be carried out after the response time or at a PM activity of one of the components (including the same component), whichever occurs first.

4.3.3 A limited number of internal maintenance workers

In practice, many firms are dealing with maintenance resource constraints (i.e. a shortage of maintenance workers). These constraints may force companies to aim for a minimal overlap of their maintenance activities. With a single internal maintenance worker, performing group maintenance is not as beneficial as in the situation where no worker constraints were assumed. With a single maintenance worker, components are replaced sequentially at a group maintenance activity. Therefore, the efficiency does not improve in the serial configuration. However, companies still gain cost benefits in terms of set-up costs of the maintenance worker. We thus assume that the economic gain obtained due to grouping maintenance activities is the same as in the experiments without worker constraints and the experiments with external maintenance workers. The maintenance policy (ABR vs. CBM) is the experimental factor here.

4.4 Analysis of the results

4.4.1 No maintenance worker constraints

Table 4-2: Performance outcomes for ideal failure prevention policy

Policy	Efficiency serial	Efficiency parallel	Total costs	Group size
ABR	98.36%	98.36%	16.58*C_{PM}	3
CBM	96.51%	98.62%	14.78*C_{PM}	1.19

Table 4-2 shows the performance results under ideal failure prevention policy and Figure 4-2 shows the maintenance schedule for ABR (top) and CBM (bottom). Under

ABR, the maintenance schedule is very regular and predictable. Preventive maintenance is performed every 60 days for all three components at the same time (average group size is 3). As a result, no blocking or starvation occurs in the serial configuration. Therefore, the efficiency in the serial configuration is equal to the efficiency in the parallel configuration (98.36%). The total maintenance costs are 16.58*C_{PM}.

By contrast, the maintenance schedule under CBM is not regular. Compared to ABR, the average time between maintenance activities is larger (72 days), since components are repaired at the time the failure is about to happen (point F in the P-F interval). Even though this leads to fewer maintenance activities for components, and thus lower maintenance costs, these activities can often not be scheduled as group maintenance activities (the average group size is 1.19). Therefore, the economic gain obtained because of grouping benefits is less. The combined effect however results in a total maintenance costs of 14.84*C_{PM}. Whereas the efficiency under CBM is slightly higher than that under ABR in the parallel configuration (98.62% vs. 98.36%, respectively) due to fewer maintenance events, it is considerably lower under CBM than under ABR in the serial configuration (96.51% vs. 98.36%) due to blocking and starving effects of maintenance events that are not synchronized under CBM.

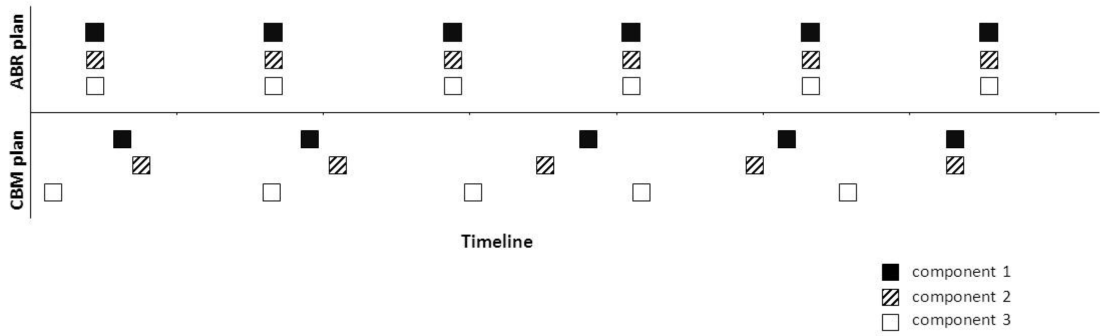

Figure 4-2: Maintenance schedule under ideal ABR (top) and ideal CBM (bottom).

Table 4-3: Performance outcomes for non- ideal failure prevention policy

Policy	Efficiency serial	Efficiency parallel	Total costs	Group size
ABR	96.82%	98.35%	17.92*C_{PM}	1.63
CBM	96.44%	98.61%	15.61*C_{PM}	1.17

Table 4-3 shows the performance results under non-ideal failure prevention policy and Figure 4-3 shows the maintenance schedule for non-ideal ABR and CBM. The results show that the inclusion of sudden failures now distorts the regular maintenance schedule under ABR. The average group size decreases to 1.63 and the total maintenance costs increase to 17.92*C_{PM}. In the parallel configuration, the efficiency is 98.35%, while blocking and starving decreases the efficiency in the serial configuration to 96.82%.

Under non-ideal CBM, the average group size decreases only marginally (1.17) and the total maintenance costs increase to 15.61*C_{PM}. In the parallel configuration, the efficiency is 98.61% and it decreases due to blocking and starving in the serial configuration to 96.44%.

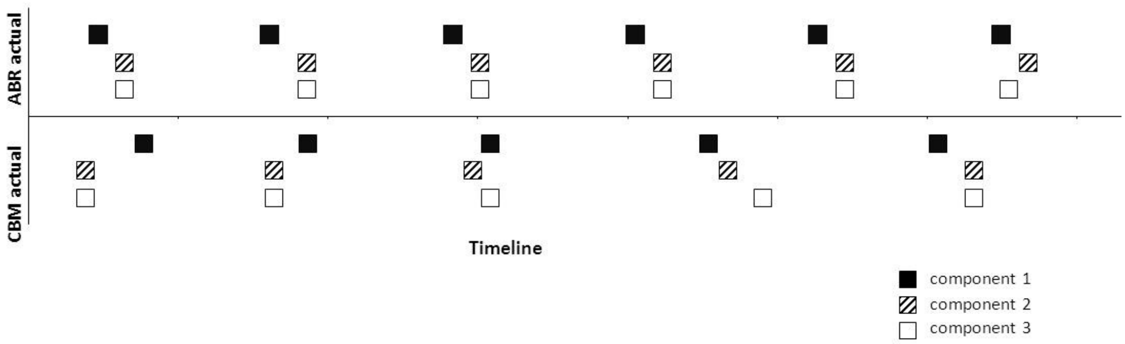

Figure 4-3: Maintenance schedule under non-ideal ABR and CBM.

In summary, the efficiency under CBM is slightly better than that under ABR in the parallel configuration, due to the larger average time between maintenance activities under CBM. In the serial configuration, the efficiency under CBM is worse than that under ABR. This can be explained by the larger extent of grouping maintenance activities under ABR, which prevents blocking and starving of components. With ideal failure prevention policy, this effect is much stronger than with non-ideal failure prevention policy. However, CBM is less costly than ABR in ideal and non-ideal failure prevention policy without worker constraints. The increased economic gain obtained under ABR (more grouping) does not outweigh the larger average time between maintenance activities under CBM. Finally, ABR results in a much more smooth maintenance plan than CBM, especially with ideal failure prevention policy.

4.4.2 External maintenance workers with a response time

Table 4-4: Performance outcomes for external maintenance workers

Policy	Response time	Efficiency serial	Efficiency parallel	Total costs	Group size	Delay
ABR	2	96.45%	98.09%	17.74*C_{PM}	1.92	1.71
	6	96.42%	97.84%	17.40*C_{PM}	2.57	3.41
	10	96.65%	97.78%	17.33*C_{PM}	2.97	3.82
	14	96.62%	97.75%	17.35*C_{PM}	3.00	3.95

CBM	2	95.77%	98.37%	15.57*C_{PM}	1.19	1.91
	6	94.66%	98.01%	15.48*C_{PM}	1.17	4.90
	10	93.51%	97.60%	15.44*C_{PM}	1.20	7.04
	14	93.00%	97.44%	15.41*C_{PM}	1.19	9.10

With external workers we only model non-ideal failure prevention policy and include a response time for maintenance workers who are called to do corrective maintenance. In Table 4-4, the performance indicators are displayed and Figure 4-4 shows the interaction effect of maintenance policy and response time on the different performance indicators. Note again that the configuration (serial or parallel) only matters with respect to efficiency.

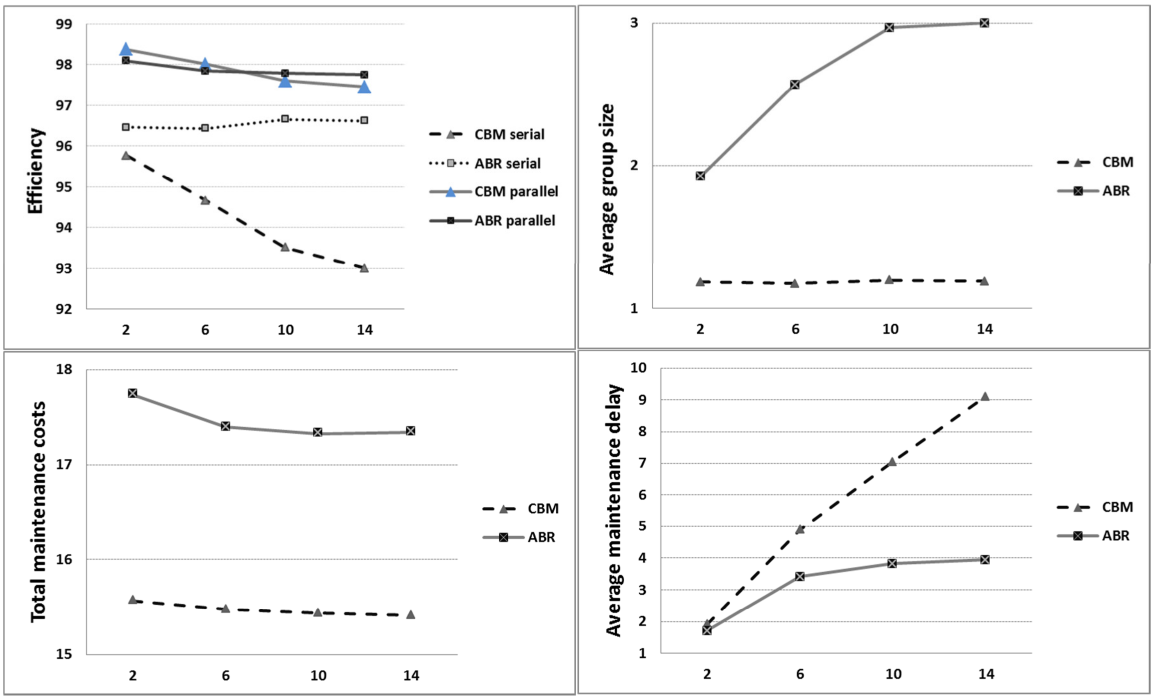

Figure 4-4: Performance results of external maintenance workers with a response time (x-axis displays different levels of response time)

The interaction effect shows that when the response time is increased, the efficiency decreases under CBM and remains about constant under ABR. When considering the configuration, the efficiency decreases most under CBM in the serial configuration, and less in the parallel configuration. For ABR, the efficiency decreases marginally in the parallel configuration and increases marginally in the serial configuration.

An explanation for the relatively stable efficiency under ABR and the decreasing efficiency under CBM when the response time is increased is as follows. Under ABR, the chance that during a response time for maintenance of a component, a PM activity for one of the other components is scheduled is higher than under CBM. The failed component can then more often be repaired before the response time, at the scheduled PM of a component. The results for the average maintenance delay and the average group size confirm this. The average delay under ABR is smaller than under CBM. A larger response time increases the grouping of maintenance activities under ABR, while it does not increase the average group size under CBM. With a response time of 10 days, almost all maintenance events are grouped under ABR, while the average group size is 1.2 under CBM. Therefore, under CBM, it is most likely that a component has to wait the entire response time after which it is maintained individually. In a serial configuration, the waiting of a single component results in blocking and/or starvation of the other components, which explains the steeper decrease in efficiency compared to the parallel configuration.

With respect to total maintenance costs, the interaction effect of maintenance policy with response time is minimal. The costs decrease under ABR with an increasing response time from 2 to 10 and then it stabilizes. This cost decrease can be explained by the economic gain that is incurred due to more group maintenance activities. Under CBM, the costs remain about constant when increasing the response time.

The maintenance schedule in Figure 4-5 shows an example of the maintenance actions for ABR (top) and CBM (bottom) with a response time of 10 days. Under ABR, an 'ideal' pattern shows up, where maintenance activities are grouped and performed at fixed time intervals. All sudden failures occur within the area of (opportunistic zone + response time) and are postponed until the next grouped PM event. This means that even though the pattern becomes regular, the efficiency is decreased compared to ideal ABR in the situation without worker constraints. The Figure also shows that under CBM, a response time of 10 days does not lead to a more regular pattern or to more grouping of maintenance actions.

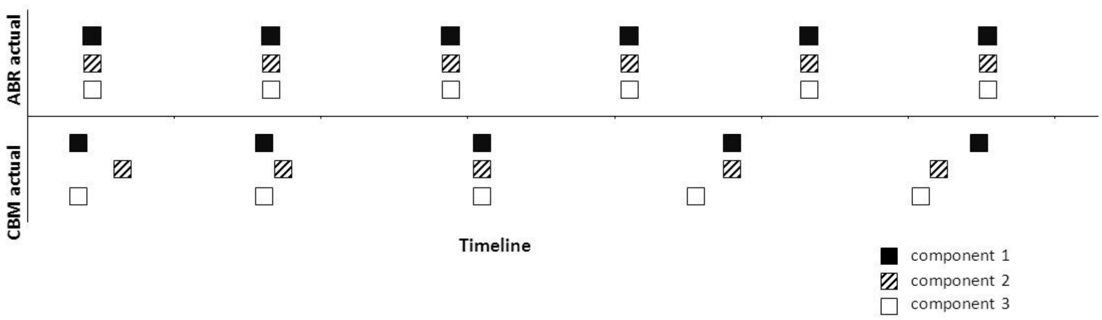

Figure 4-5: Maintenance schedule under ABR and CBM with external maintenance workers and a response time of 10 days.

In summary, the use of external workers with a response time decreases the efficiency under CBM and more in the serial configuration than in the parallel configuration. By contrast, under ABR it also increases the grouping of maintenance activities, which absorbs the negative effect of longer response times on efficiency in the serial configuration. Furthermore, since more PM activities are scheduled under ABR better than under CBM, the chance that a CM activity can be combined with a scheduled PM activity during the response time is larger. This limits the average delay time under ABR, which positively affects the efficiency.

With a small response time, the efficiency under CBM is larger than that under ABR in the parallel configuration, due to the larger average time between maintenance activities under CBM. If the response time increases, the efficiency benefits of the smaller average delay times under ABR outweighs the larger average time between maintenance activities under CBM. In the serial system, the blocking and starving effects when waiting for external maintenance workers under CBM and the inability to group maintenance activities negatively affects the efficiency. With respect to costs, CBM performs better than ABR. Increasing the response time slightly decreases the costs under ABR, because of the economic gain incurred due to more group maintenance activities, while the costs remain constant under CBM. Finally, the increased grouping of maintenance activities under ABR when increasing the response time, results in a more smoothed maintenance plan than under CBM.

4.4.3 A limited number of internal maintenance workers

With a single internal maintenance worker, we focus on the effect of maintenance policy in the parallel and serial configuration.

Table 4-5: Performance outcomes for internal maintenance workers

Policy	Efficiency serial	Efficiency parallel	Total costs	Group size
ABR	95.07%	98.34%	18.04*C_{PM}	1.65
CBM	95.83%	98.58%	15.77*C_{PM}	1.17

The results (see Table 4-5) show that the effect of maintenance policy is significant for all performance measures and CBM performs better than ABR for efficiency and for total maintenance costs. Since the components are replaced sequentially with group maintenance activities, the larger average group size of ABR (1.65) compared to CBM (1.17) does not affect the efficiency in the serial configuration. This also explains the lower efficiency of the serial configuration with a single internal maintenance worker under CBM and especially under ABR compared to that of the serial configuration without maintenance worker constraints. Due to the larger average time between maintenance activities under CBM, the efficiency of CBM is higher than that of ABR in the serial configuration (95.83% vs. 95.07%) and in the parallel configuration (98.58% vs. 98.34%).

The total maintenance costs are lower under CBM (15.77*C_{PM}) than under ABR (18.04*C_{PM}). The larger economic gains due to more grouping in ABR do not cover the extra costs of more PM activities.

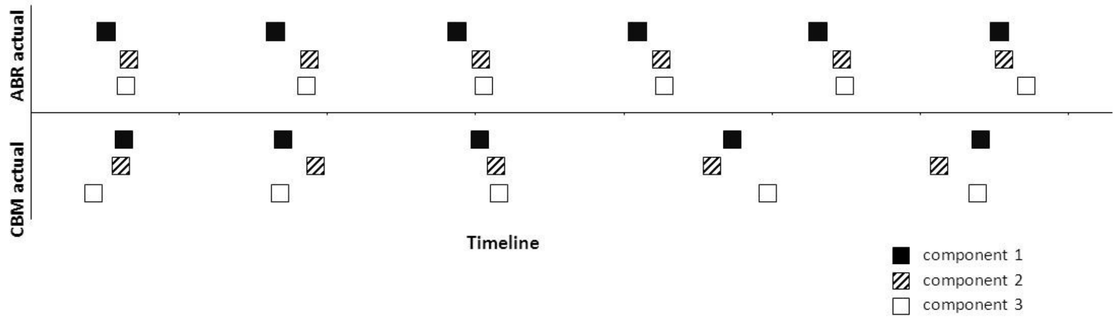

Figure 4-6: Maintenance schedule under ABR and CBM with a limited number of internal maintenance workers.

The maintenance schedule in Figure 4-6 shows an example of the maintenance activities for ABR and CBM using one internal maintenance worker. When maintenance activities are grouped, the activities are scheduled sequentially. In the Figure, this is displayed as a slight difference in the start moment of the squares. For instance, the first maintenance activities of component 2 and 3 under ABR are grouped, where component 3 is maintained first in 24 hours and component 2 directly thereafter in the next 24 hours. The Figure shows that in ABR there are more maintenance activities than in CBM, and more activities are grouped (sequentially).

In summary, with a limited number of internal maintenance workers, the efficiency benefits of grouping maintenance in the serial configuration disappears. CBM here outperforms ABR with respect to efficiency and (to a larger extent) costs.

4.5 Conclusions

In this chapter, we have studied the impact of using CBM or ABR in serial and parallel multi-component systems for three situations with different types of maintenance resources and their associated limitations. We have studied a situation without worker constraints, a situation with external maintenance workers with a response time, and a situation with a single internal maintenance worker. As performance indicators, we looked at the efficiency, the total maintenance costs, and the smoothness of the maintenance plans.

The results show that within the current experimental settings, CBM is often not able to group maintenance activities as well as ABR, resulting in a lower efficiency in the serial configuration due to blocking and starving effects. Where ABR is able to group all maintenance activities (i.e. with ideal failure prevention policy without worker constraints and with external workers and a long response time), the efficiency advantages of ABR over CBM in the serial configuration are especially large. With a single internal maintenance worker, the sequential execution of maintenance activities does not affect the efficiency in the serial system and here CBM performs better. In the parallel configurations, CBM performs better with respect to efficiency than ABR, due to the larger mean time between maintenance activities under CBM. However, with external maintenance workers the efficiency benefits of the smaller average delay times under ABR outweigh the larger average time between maintenance activities under CBM if the response time is large.

With respect to total maintenance costs, we found that CBM performs better than ABR in all situations. The larger average time between maintenance activities under CBM results in fewer maintenance activities and thus in lower maintenance costs. The economic gain that is obtained with a larger number of grouped maintenance activities in specific situations is never large enough to reverse this conclusion.

Finally, ABR seems to result in a more smooth maintenance plan than CBM, especially without maintenance worker constraints and ideal failure prevention policy and with external workers with a long response time.

CHAPTER 5

Extensions

In this chapter additional experimental factors are analyzed as extensions to the research presented in Chapters 2 and 3.

5.1 Overview

As mentioned in the thesis outline (section 1.5.5), the Chapters 2 to 4 are based on papers that are either published or under review at peer reviewed journals. In this chapter, we include additional experiments that were conducted for the research in Chapters 2 and 3 but were not presented in the related papers.

Two new experimental factors are included in this chapter: 1) the corrective to preventive maintenance cost ratio; 2) the MTTR-MTBF ratio. Besides these factors, we increased the range of PED values for the research presented in Chapter 3.

5.1.1 Corrective to preventive maintenance cost ratio

The corrective to preventive maintenance cost ratio (Cc-Cp ratio) is one of the parameters that is used in selecting maintenance policies and in defining PM intervals. Due to urgent actions in corrective maintenance events, the corrective maintenance costs are usually higher than the costs that are incurred for preventive maintenance and thus the Cc-Cp ratio is usually larger than one. In Chapter 2 we used a fixed Cc-Cp ratio of 2 and in Chapter 3 we used a fixed ratio of 1.5.

In this chapter, we investigate the effect of the Cc-Cp ratio on the performance indicators that are developed for the research in Chapters 2 and 3. The Cc-Cp ratios investigated are 1.5, 2, 2.5, and 3.

5.1.2 MTTR-MTBF ratio

The mean time between failures (MTBF) is the predicted elapsed time between inherent failures of a system during operation. The larger the value of MTBF, the more reliable is the system. The mean time to repair (MTTR) is the average time required to repair a failed component. A larger MTTR-MTBF ratio results in a lower system availability.

In our models (Chapters 2 to 4), the MTTR is fixed (but varies in different chapters) and the component failures occur according to a gamma distribution with a MTBF of 72 days. To define new values for the MTTR-MTBF ratio, we had two options to either change the MTFB or to change the MTTR. We chose the latter and conducted new sets of experiments with a MTTR of 12, 24, 36 and 48 hrs.

For ease of use, we considered 12 hrs as a default value for MTTR. This means that the corresponding MTTR-MTBF ratio equals 0.00694 (12hr/(72*24 hr)). This value is considered as the default value for the MTTR-MTBF ratio and will be shown as “x”.

In Chapter 2 the MTTR was fixed at 12 hrs. Chapter two thus displays the results for a MTTR-MTBF ratio of 1x. In Chapter 3 the MTTR was fixed at 24 hrs, or in other words a MTTR-MTBF ratio of 2x. In this chapter we investigate the range 1x, 2x, 3x and 4x.

5.2 Extension to Chapter 2

As shown in Table 5-1, the model in Chapter 2 was extended by adding two additional experimental factors. In total seventy two experiments (three maintenance policies (PL) x two degrees of coupling (PC) x three chances of failure occurrence (CFO) x four levels of MTTR-MTBF ratio) were performed. Cc-Cp ratio only affects the total maintenance cost. Hence, to reduce the simulation time, the number of maintenance (corrective and preventive) events has been collected as a performance indicator. Then the effect of Cc-Cp ratio on the total cost has been calculated in MS. Excel.

The simulation time, number of runs, warm up period etc. are identical to the settings in Chapter 2.

Table 5-1: Additional experimental factors and their levels for Chapter 2

Cc-Cp Ratio Corrective to preventive maintenance cost ratio	1.5	2	2.5	3

MTTR-MTBF Ratio Mean time to repair over mean time between failure ratio	1x	2x	3x	4x

5.2.1 Total maintenance cost

In Chapter 2, the effect of PL, CFO and their interaction (PL x CFO) on the total maintenance cost has been investigated. In this section, the focus will be on the effect of Cc-Cp and MTTR-MTBF ratios. Since the production context has no effect on the performance indicator total maintenance cost, it is not included as an independent variable.

Table 5-2: ANOVA results of significant effects on total maintenance cost

Source	***Total maintenance costs***	
	F	***p- value***
PL	72532.3	<0.001
CFO	37164.8	<0.001
Cc-Cp ratio	5529.2	<0.001
MTTR-MTBF ratio	47.4	<0.001
PL * CFO	7704.1	<0.001
PL * Cc-Cp ratio	1382.6	<0.001
CFO * Cc-Cp ratio	1078.4	<0.001
CFO * MTTR-MTBF ratio	23.4	<0.001
PL * MTTR-MTBF ratio	12.0	<0.001
PL * CFO * Cc-Cp ratio	269.6	<0.001

PL * CFO * MTTR-MTBF ratio	12.8	<0.001

As can be seen in Table 5-2, both Cc-Cp and MTTR-MTBF ratios significantly affect total maintenance cost. However, the effect of the cost ratio (Cc-Cp) (F value of 5529.2) is much larger than the effect of the MTTR-MTBF ratio (F value of 47.4).

In a fixed period of time, components under CBM will have less maintenance events than components under BR or under ABR. Therefore, CBM has the best performance and BR has the worst performance on the total maintenance cost. Besides, the interaction of CFO and PL showed that CFO significantly affects the total annual maintenance costs for BR, while it is less influential for CBM (see section 2.6.1.1). The significance of Cc-Cp ratio relates to the number of maintenance events due to using a specific maintenance policy. Figure 5-1 shows the interaction effect of PL, CFO, and Cc-Cp ratio (PL x CFO x Cc-Cp). This three-way interaction significantly affects the total maintenance cost ($p<0.001$) with an F value of 269.6. In all Cc-Cp values, BR has the worst performance, ABR is in the middle and CBM has the best performance on total maintenance cost. Increasing Cc-Cp ratio results in higher maintenance costs. However, this factor only affects BR and ABR. In the model, only PM activities will be done for a component under CBM policy. Therefore, increasing the Cc-Cp ratio does not have any effect on total maintenance cost under CBM. As expected, a larger CFO creates a higher chance of corrective maintenance and consequently higher maintenance cost. By increasing the Cc-Cp ratio from 1.5 to 3, the total maintenance cost under BR increase 35.6% for CFO: 5% and 66.8% for CFO: 30%. This increase under ABR is 13.3% for CFO: 5% and 47.2% for CFO: 30%, which is less than under BR.

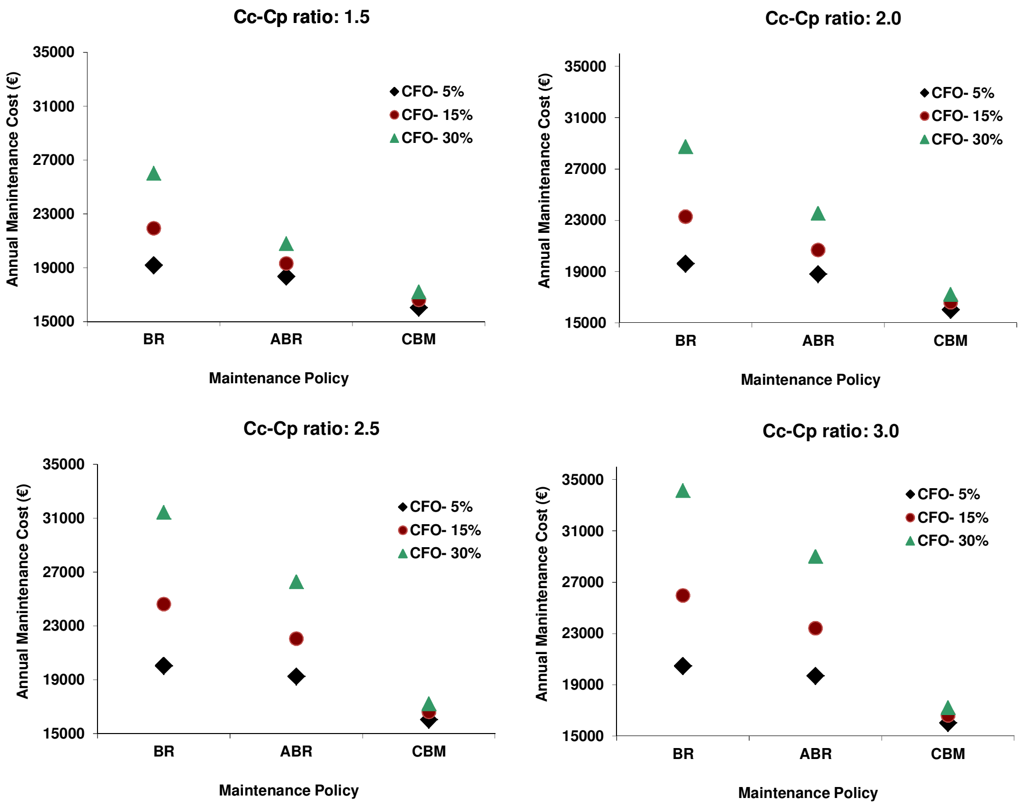

Figure 5-1: PL - CFO - Cc-Cp ratio interaction effect on total annual maintenance cost

The MTTR-MTBF ratio also affects the total maintenance cost. Increasing this factor results in lower total maintenance cost. As we modeled it, a larger ratio represents longer repairs, which means less maintenance events and consequently lower maintenance cost. The interaction effect of PL, CFO, and MTTR-MTBF ratio (PL x CFO x MTTR-MTBF ratio) is shown in Figure 5-2. Although this three-way interaction is significant ($p<0.001$) its effect is substantially lower than the interaction effect of PL x CFO x Cc-Cp. CBM has the lowest total maintenance cost in all MTTR-MTBF ratios and BR has the worst performance. A further analysis of the PL x CFO x MTTR-MTBF interaction shows that the effect of the MTTR-MTBF ratio is very small and not unidirectional within each combination of PL and CFO. This can also be seen in Figure 5-2.

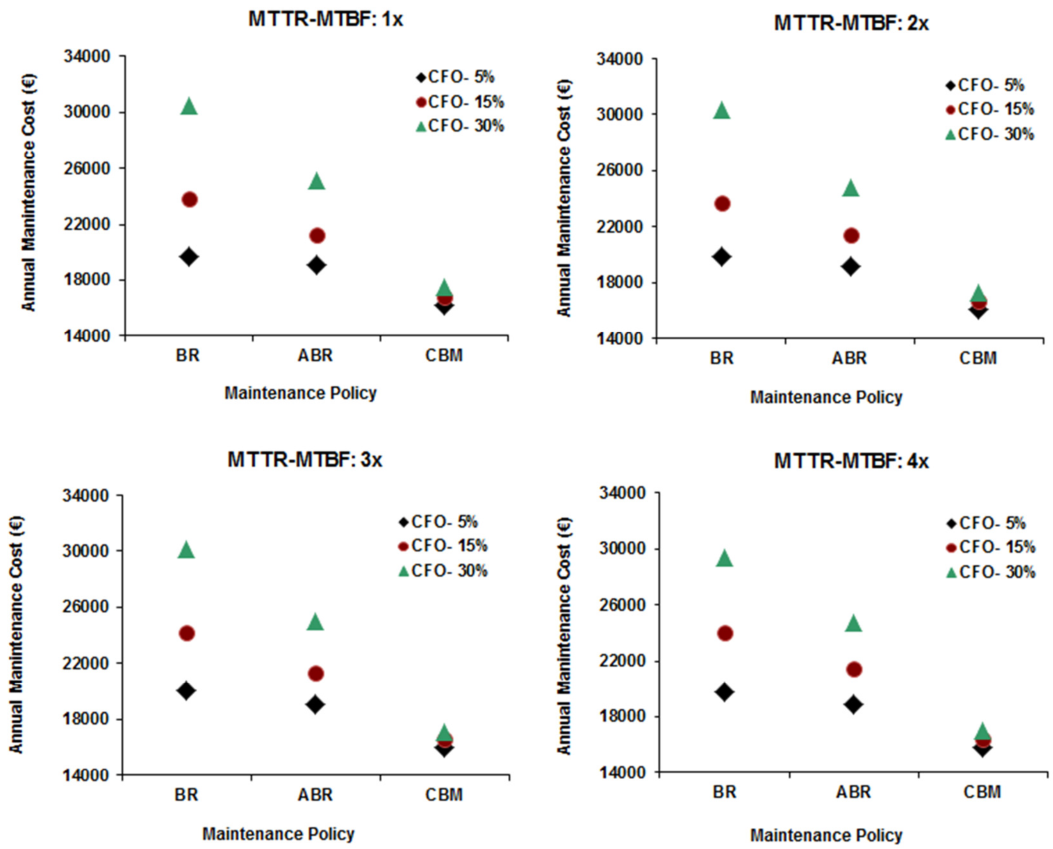

Figure 5-2: PL – CFO – MTTR-MTBF ratio interaction effect on total annual maintenance cost

5.2.2 System availability

As it discussed in section 2.6.1, the production context does not affect system availability. Between the two newly introduced experimental factors (i.e. the MTTR-MTBF ratio and the Cc-Cp ratio), only the MTTR-MTBF ratio affects system availability. The Cc-Cp ratio does not have any effect on this performance indicator.

Table 5-3: ANOVA results of significant effects on system availability

Source	***System Availability***	
	F	***p- value***
MTTR-MTBF ratio	2305962.0	<0.001
PL	90881.9	<0.001
CFO	19684.3	<0.001
PL * CFO	7080.3	<0.001
PL * MTTR-MTBF ratio	3725.8	<0.001
CFO * MTTR-MTBF ratio	627.8	<0.001
PL * CFO * MTTR-MTBF ratio	169.3	<0.001

Table 5-3 shows that the MTTR-MTBF ratio and its interactions significantly affect system availability. The main effect of MTTR-MTBF ratio (F value of 2305962.0) is larger than the effect of other experimental factors like PL (F value of 90881.9) or CFO (F value of 19684.3). This can be explained by the fact that increasing the MTTR-MTBF ratio in our modeling means an increase in MTTR, which results in a decrease of the uptime period of the component and consequently a decrease in system availability (see Figure 5-3).

As explained in section 2.6.1, CBM has the highest system availability in comparison with BR and ABR. Also, the interaction of PL and CFO showed that CFO has a minimal effect on availability in ABR, a larger effect in CBM, and the largest effect in BR. A quick glance at Figure 5-3 shows a similar pattern of PL and CFO interactions for different MTTR-MTBF ratios. The only difference is that increasing the MTTR-MTBF ratio from 1x to 4x increases the difference between CFOs of various policies and mainly under BR and CBM. For MTTR-MTBF: 1x, the system availability difference between CFO: 5% and CFO: 30% in BR, ABR and CBM are 0.4%, 0.0% and 0.1%. These differences increase to 0.9%, 0.1% and 0.4% for MTTR-MTBF: 4x.

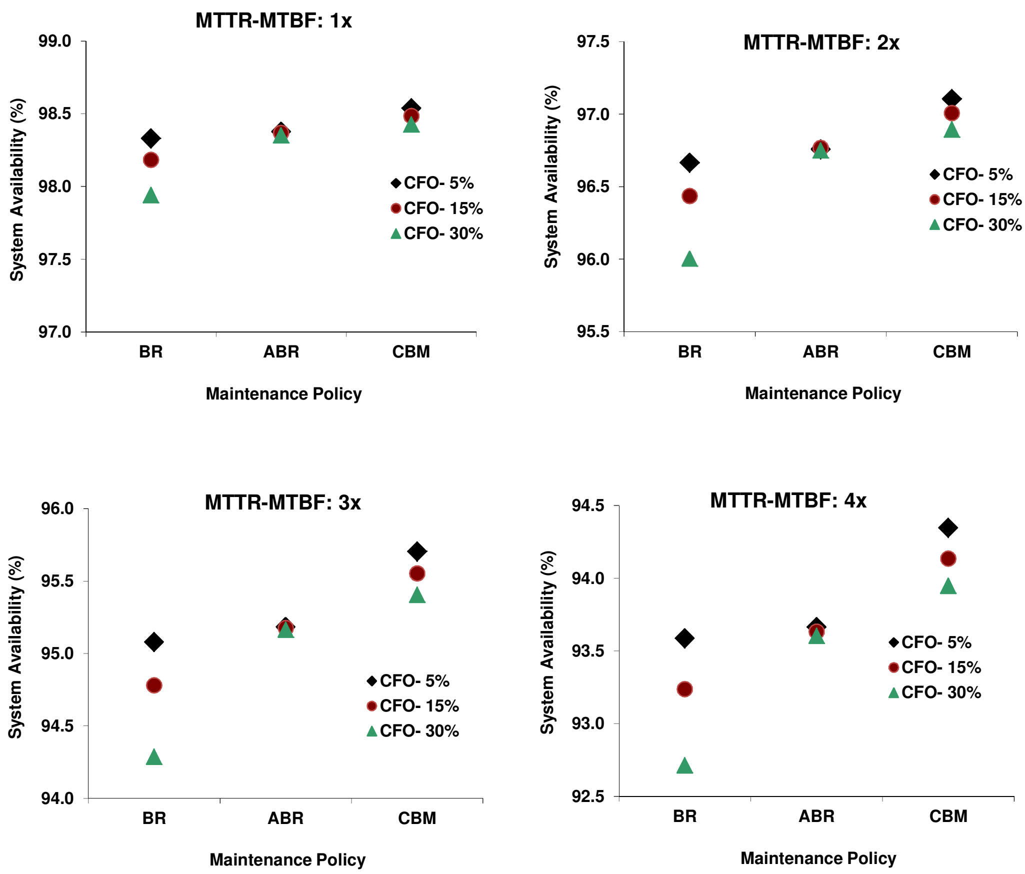

Figure 5-3: PL – CFO – MTTR-MTBF ratio interaction effect on system availability

5.2.3 Line efficiency

To simplify the analysis of line efficiency, the results have been separated for the two production contexts (i.e. loosely coupled processes and tightly coupled processes). Moreover, since the Cc-Cp ratio only affects total maintenance cost, it has not been included in the analysis.

5.2.3.1 Loosely coupled processes

Table 5-4 shows the significant main and interaction effect of maintenance policy (PL), chance of failure occurrence (CFO) and the MTTR-MTBF ratio as independent variables and line efficiency as dependent variable for loosely coupled processes.

Table 5-4 ANOVA results of significant effects on line efficiency for loosely coupled processes

Source	***Line efficiency***	
	F	***p- value***
MTTR-MTBF ratio	674921.6	<0.001
PL	32482.6	<0.001
CFO	6929.2	<0.001
PL * CFO	2778.1	<0.001
PL * MTTR-MTBF ratio	1380.9	<0.001
CFO * MTTR-MTBF ratio	257.6	<0.001
PL * CFO * MTTR-MTBF ratio	77.6	<0.001

Table 5-4 shows that all the independent variables and their interactions significantly affect line efficiency and the MTTR-MTBF ratio has the largest effect with an F value of 674291.6.

Under loosely coupled processes, there is no blocking and starvation. Therefore, the results for line efficiency are similar to those of system availability. CBM has the best and BR has the worst performance on line efficiency. As explained in section 2.6.2, CFO has a minimal effect under ABR, a larger effect under CBM, and the largest effect under BR. The MTTR-MTBF ratio has a significant negative effect on line efficiency. Increasing this ratio decreases the uptime period of the system and consequently decreases line efficiency. The average decrease (for all CFOs) under BR, ABR and CBM is 2.6%, 2.4% and 2.2 % respectively, when increasing the ratio from 1x to 4x.

The three–way interaction of PL x CFO x MTTR-MTBF ratio is depicted in Figure 5-4. Increasing the MTTR-MTBF ratio enlarges the gap between various CFOs in different policies and mainly under BR and CBM. At MTTR-MTBF: 1x, the difference between line efficiency for CFO: 5% and CFO: 30% for BR, ABR and

CBM are 0.2%, 0.0% and 0.1%. When we increase MTTR-MTBF from 1x to 4x, these differences increases and for BR, ABR and CBM becomes 0.6%, 0.03 and 0.2%.

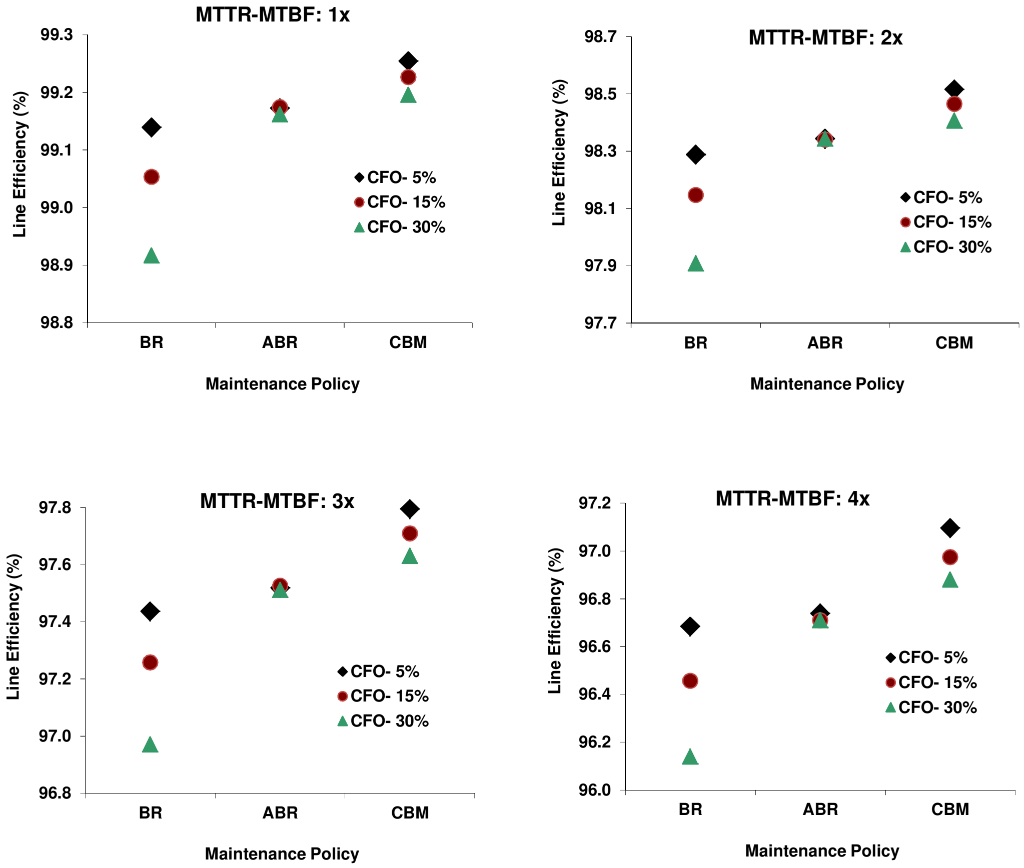

Figure 5-4: PL – CFO – MTTR-MTBF ratio interaction effect on line efficiency for loosely coupled processes

5.2.3.2 Tightly coupled processes

Table 5-5: ANOVA results of significant effects on line efficiency for tightly coupled processes

Source	***Line efficiency***	
	F	***p- value***
MTTR-MTBF ratio	117066.0	<0.001
PL	28937.2	<0.001
CFO	3100.0	<0.001
PL * MTTR-MTBF ratio	1845.7	<0.001
PL * CFO	462.7	<0.001
CFO * MTTR-MTBF ratio	177.1	<0.001
PL * CFO * MTTR-MTBF ratio	20.8	<0.001

Under tightly coupled processes, blockage and starvation decrease LE compared to loosely coupled processes. BR becomes the most efficient policy, then CBM and finally ABR. As discussed in section 2.6.2, increasing CFO adversely affects LE and this effect is larger under tightly coupled processes than under loosely coupled processes.

Similar to loosely coupled processes, the MTTR-MTBF ratio has a significant negative effect on LE. This ratio has the worst effect under ABR, an 8.6 % decrease in LE when going from 1x to 4x, compared to an 8.4% and 5.6% decrease under CBM and BR.

The effect of the MTTR-MTBF ratio on PL x CFO is shown in Figure 5-5. In MTTR-MTBF: 1x, the LE gap between CFO: 5% and 30% for BR, ABR and CBM is 0.8%, 0.2% and 0.2%, respectively. Increasing the MTTR-MTBF ratio enlarges this gap and has the worst effect under ABR.

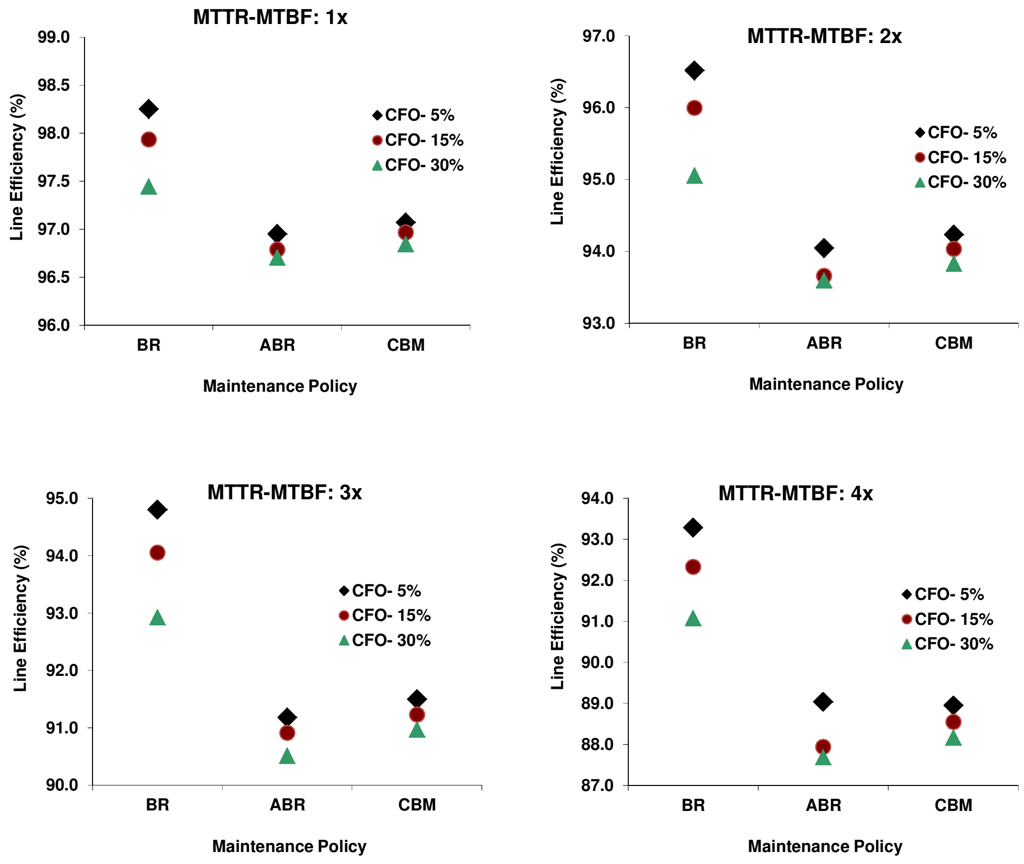

Figure 5-5: PL – CFO – MTTR-MTBF ratio interaction effect on line efficiency for tightly coupled processes

5.3 Extension to Chapter 3

The corrective to preventive maintenance cost ratio (Cc-Cp ratio), the MTTR-MTBF ratio and the percentage of positive economic dependency (PED) are the three independent variables experimented with in this section as an extension to Chapter 3 (see Table 5-6). In total ninety-six experiments (four N-CBM x three LOZ x two CF-PM x four MTTR-MTBF) are performed with the simulation model. The effect of PED and the Cc-Cp ratio is calculated in a spread sheet by multiplying their values with the number of maintenance events (preventive, corrective and group) as collected in the simulation experiments.

Table 5-6: Additional experimental factors and their levels for Chapter 3

Cc-Cp Ratio Corrective to preventive maintenance cost ratio	1.5	2	2.5	3
MTTR-MTBF Ratio Mean time to repair over mean time between failure ratio	1x	2x	3x	4x
PED Positive economic dependency	10%	20%	30%	40%

5.3.1 Line productivity

PED and the Cc-Cp ratio do not influence the number of maintenance events and only affect total maintenance cost. Therefore, they were excluded in the line productivity analyses.

Table 5-7: ANOVA results of significant effects on line productivity

Source	***Line Productivity***	
	F	***p- value***
MTTR-MTBF ratio	34956.1	<0.001
LOZ	8330.4	<0.001
CF-PM	749.5	<0.001
N_CBM	185.6	<0.001
LOZ * MTTR-MTBF ratio	481.5	<0.001
N_CBM * LOZ	425.8	<0.001
N_CBM * CF-PM	287.4	<0.001
LOZ * CF-PM	96.1	<0.001
CF-PM * MTTR-MTBF ratio	46.0	<0.001
N_CBM * MTTR-MTBF ratio	10.4	<0.001
N_CBM * LOZ * CF-PM	39.8	<0.001

N_CBM * LOZ * MTTR-MTBF ratio	25.5	<0.001
N_CBM * CF-PM * MTTR-MTBF ratio	18.5	<0.001
LOZ * CF-PM * MTTR-MTBF ratio	5.4	<0.001
N_CBM * LOZ * CF-PM * MTTR-MTBF ratio	2.1	0.004

Table 5-7 shows the significant effect of the experimental factors and their interactions on LP. In Chapter 3, the effects of N_CBM, LOZ, CF-CP and their interactions have been investigated for a fixed level of the MTTR-MTBF ratio of 2x. To keep the analysis consistent with section 3.5.1 and to visualize the effects of the MTTR-MTBF ratio, we will again focus on the three-way inaction of N-CBM x LOZ x CF-PM but now display these results for each level of the MTTR-MTBF ratio (see Figure 5-6).

By increasing the MTTR-MTBF ratio (which means longer repairs in our modeling), the total repair time increases and consequently LP decreases. The extent of this effect depends on LOZ, CF-PM, and N-CBM.

For all MTTR-MTBF ratios, the worst LP is found in an all ABR system (N-CBM=0) with a large CF-PM. Under MTTR-MTBF: 4x, LP equals 90.4% (see Figure A-6). As explained in section 3.5.1, increasing the number of components under CBM (N-CBM) results in a higher LP without opportunistic maintenance, but it may decrease LP with opportunistic maintenance, especially for all ABR systems that move to a few components using CBM. Increasing the opportunistic zone thus mainly improves LP when components use ABR. Increasing the MTTR-MTBF ratio decreases LP and the interaction effects with other independent variables are small (see Table 5-7). The difference between the effect of 10% and 20% CF-PM seems to increase for the all ABR systems. Also the differences between similar maintenance policies (N-CBM=0 or N-CBM=3) and dissimilar maintenance policies (N-CBM=1 or N-CBM=2) seems to increase when increasing the MTTR-MTBF ratio. Finally, if the MTTR-MTBF ratio increases, the difference of applying opportunistic maintenance in all ABR systems compared to systems with components under CBM seems to increase. With a large MTTR-MTBF ratio, an all ABR system combined with an opportunistic maintenance strategy would thus be even more preferred with respect to LP, especially if CF-PM is low.

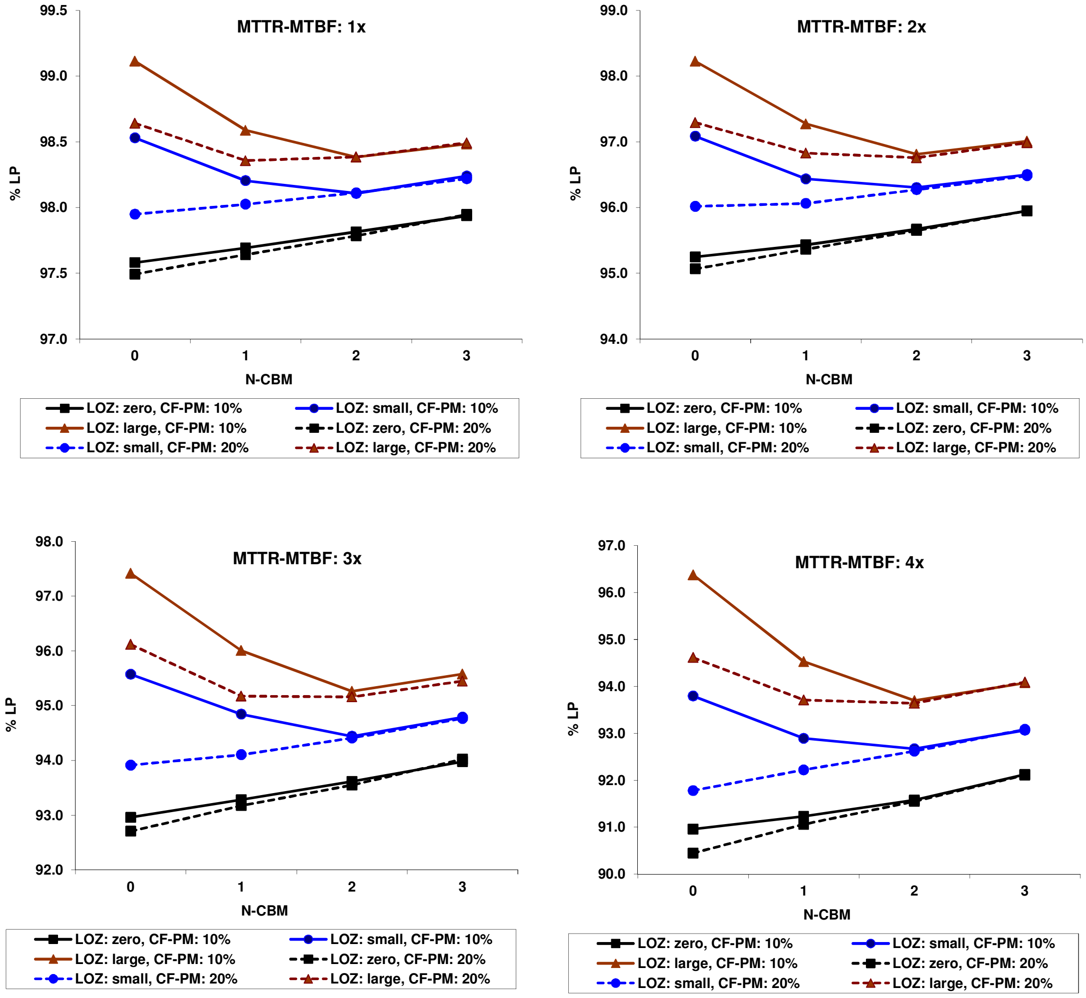

Figure 5-6: The interaction effect of N-CBM, LOZ, CF-PM and MTTR-MTBF ratio on line productivity

5.3.2 Total maintenance cost

The significant effects of the independent variables and their interactions on the total maintenance cost are shown in Table 5-8. The effect of the experimental factors N-CBM, LOZ, CF-PM, and PED is already presented and discussed in section 3.5.2. Hence, the focus will be on the MTTR-MTBF and Cc-Cp ratios and on the extended range of PED values. In line with section 3.5.2, the effect of including these factors on the annual maintenance costs will be investigated by analyzing the N-CBM x LOZ x CF-PM interaction effect for different levels of the newly included experimental factors.

Table 5-8: ANOVA results of significant effects on total maintenance cost

Source	***Total maintenance cost***	
	F	***p- value***
N_CBM	264,027.5	<0.001
CF_PM	96,796.8	<0.001
LOZ	31,455.8	<0.001
Cc-Cp ratio	31,420.8	<0.001
PED	8,094.3	<0.001
MTTR-MTBF ratio	925.7	<0.001
N_CBM * CF_PM	20,428.9	<0.001
N_CBM * Cc-Cp ratio	5,932.1	<0.001
CF_PM * Cc-Cp ratio	3,739.3	<0.001
LOZ * PED	2,580.6	<0.001
N_CBM * LOZ	2,552.5	<0.001
N_CBM * PED	347.6	<0.001
LOZ * CF_PM	302.1	<0.001
CF_PM * PED	119.5	<0.001
LOZ * Cc-Cp ratio	29.9	<0.001
LOZ * MTTR-MTBF ratio	17.8	<0.001
CF_PM * MTTR-MTBF ratio	16.2	<0.001
N_CBM * MTTR-MTBF ratio	14.3	<0.001
N_CBM * CF_PM * Cc-Cp ratio	697.2	<0.001
N_CBM * LOZ * CF_PM	152.5	<0.001
N_CBM * LOZ * PED	109.3	<0.001
N_CBM * CF_PM * PED	50.9	<0.001
LOZ * CF_PM * PED	27.7	<0.001
LOZ * CF_PM * MTTR-MTBF ratio	16.5	<0.001
N_CBM * LOZ * MTTR-MTBF ratio	14.1	<0.001
N_CBM * CF_PM * MTTR-MTBF ratio	9.4	<0.001
LOZ * CF_PM * Cc-Cp ratio	5.3	<0.001
N_CBM * LOZ * Cc-Cp ratio	4.3	<0.001
N_CBM * LOZ * CF_PM * MTTR-MTBF ratio	13.5	<0.001
N_CBM * LOZ * CF_PM * PED	12.1	<0.001
N_CBM * LOZ * CF-PM * Cc-Cp ratio	2.3	0.002

All the three experimental factors that are introduced in this chapter (i.e. PED, MTTR-MTBF ratio and Cc-Cp ratio) and their interactions with the previously investigated experimental factors have significant effects on total maintenance cost. Among these factors, the Cc-Cp ratio has the largest effect with an F value of 31,420.8.

The Cc-Cp ratio is a coefficient of corrective maintenance events (see equation 3-3)[6] in calculating total maintenance cost. In the model, no corrective maintenance actions occur for the components under CBM. Therefore, in N_CBM: 3, the Cc-Cp ratio does not affect the total maintenance cost system at all. In the configurations with at least one component under ABR, increasing this ratio results in a higher total maintenance cost. As explained in section 3.5.2, applying opportunistic maintenance results in more group maintenance and less corrective maintenance events. Therefore, the effect of the Cc-Cp ratio is larger without opportunistic maintenance (LOZ: 0) than with opportunistic maintenance. Figure 5-7, shows that the highest maintenance cost (25.6*CPM) occurs without opportunistic maintenance (LOZ: 0), when all the components use ABR (N-CBM:0), CF-PM equals 20% and the Cc-Cp ratio equals 4x.

Compared to the Cc-Cp ratio, PED has a reverse effect on total maintenance cost. By increasing PED, the total maintenance cost decrease for systems with opportunistic maintenance. As explained in section 3.5.2, most group maintenance events occur in large LOZ and when all the components use ABR. Consequently PED has the largest effect in this scenario (see Figure 5-8).

Although the MTTR-MTBF ratio has a significant effect on the total maintenance cost, its main effect (F value of 925.7) is smaller than that of the Cc-Cp ratio and of PED. Increasing the MTTR-MTBF ratio increases the total repair time, which decreases the chance of corrective maintenance to occur. As shown in Figure 5-9, increasing the MTTR-MTBF ratio results in a small cost saving.

[6] In chapter 3, a fixed Cc-Cp ratio: 1.5 is used.

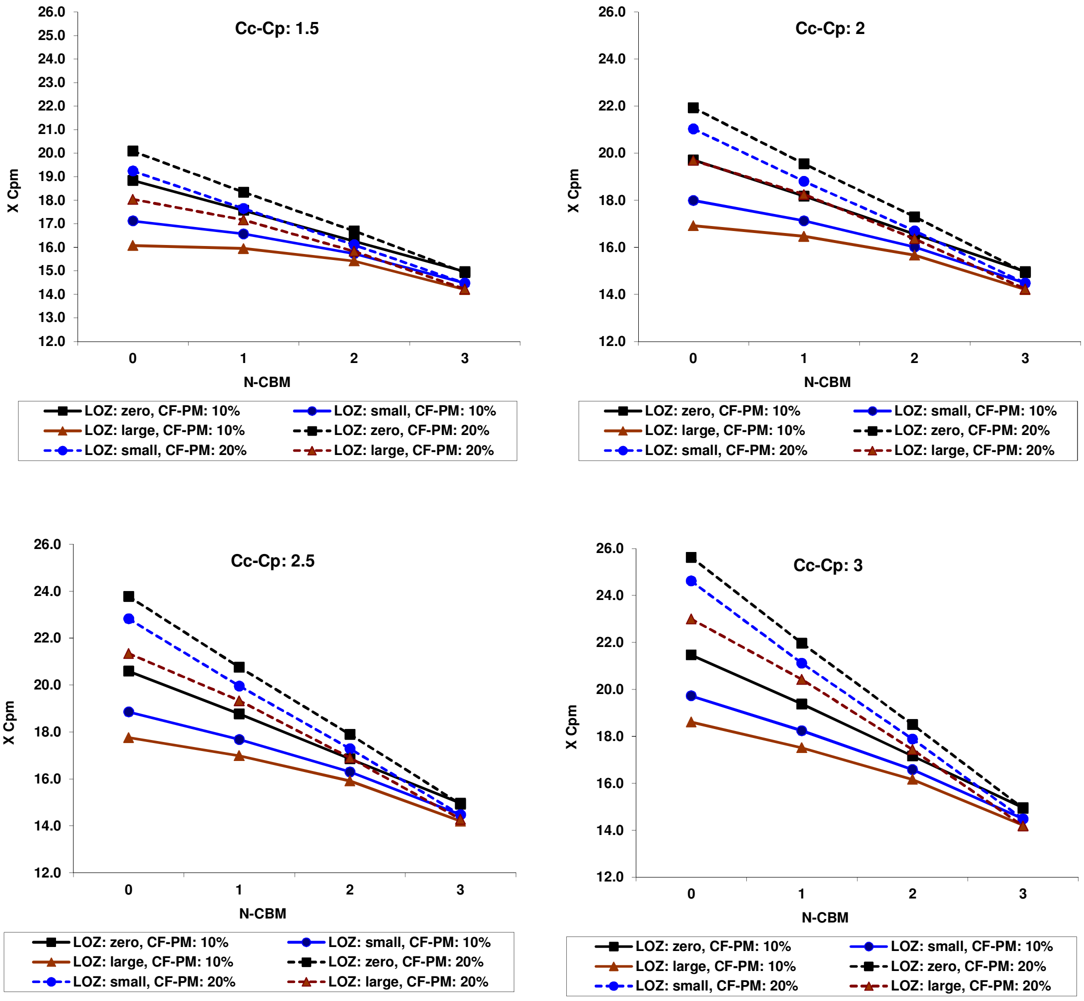

Figure 5-7: The interaction effect of N-CBM, LOZ, CF-PM and Cc-Cp ratio on annual maintenance cost

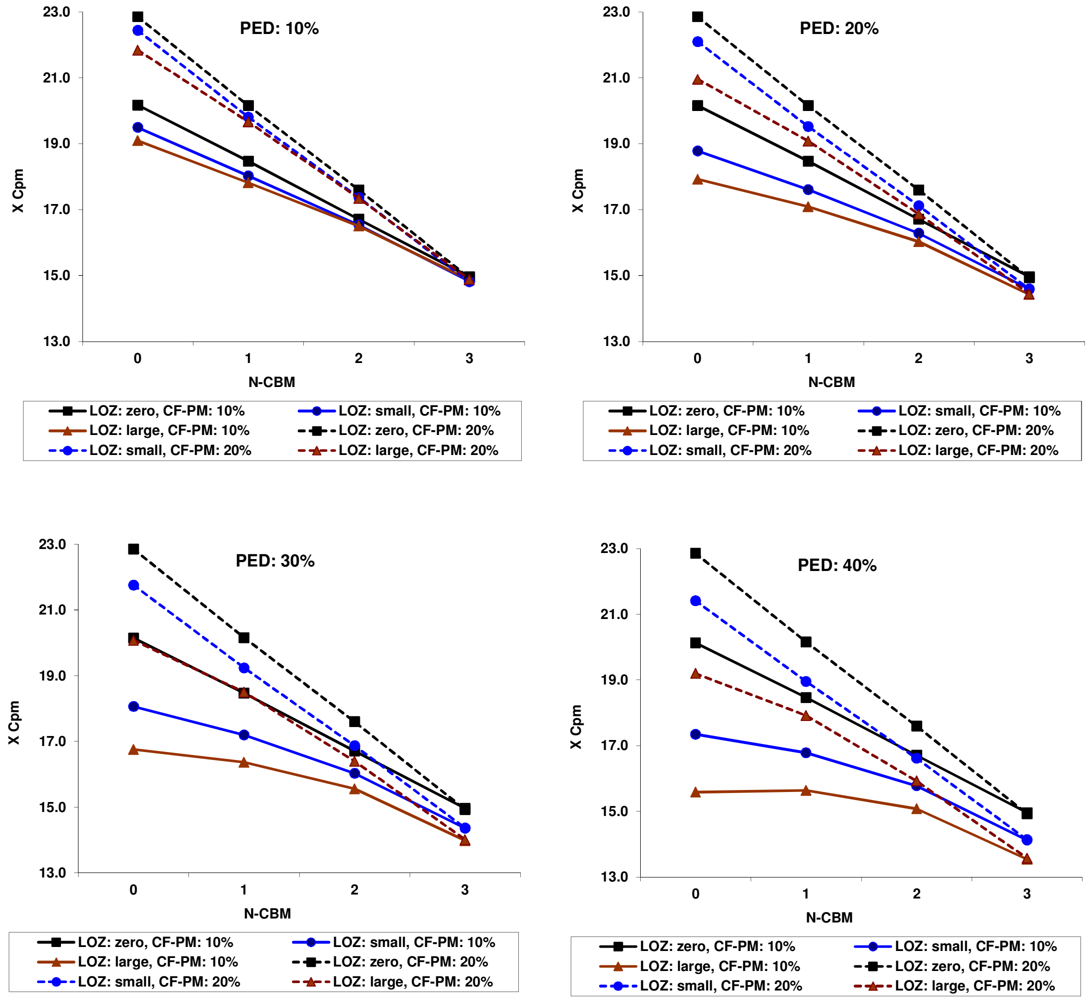

Figure 5-8: The interaction effect of N-CBM, LOZ, CF-PM and PED ratio on annual maintenance cost

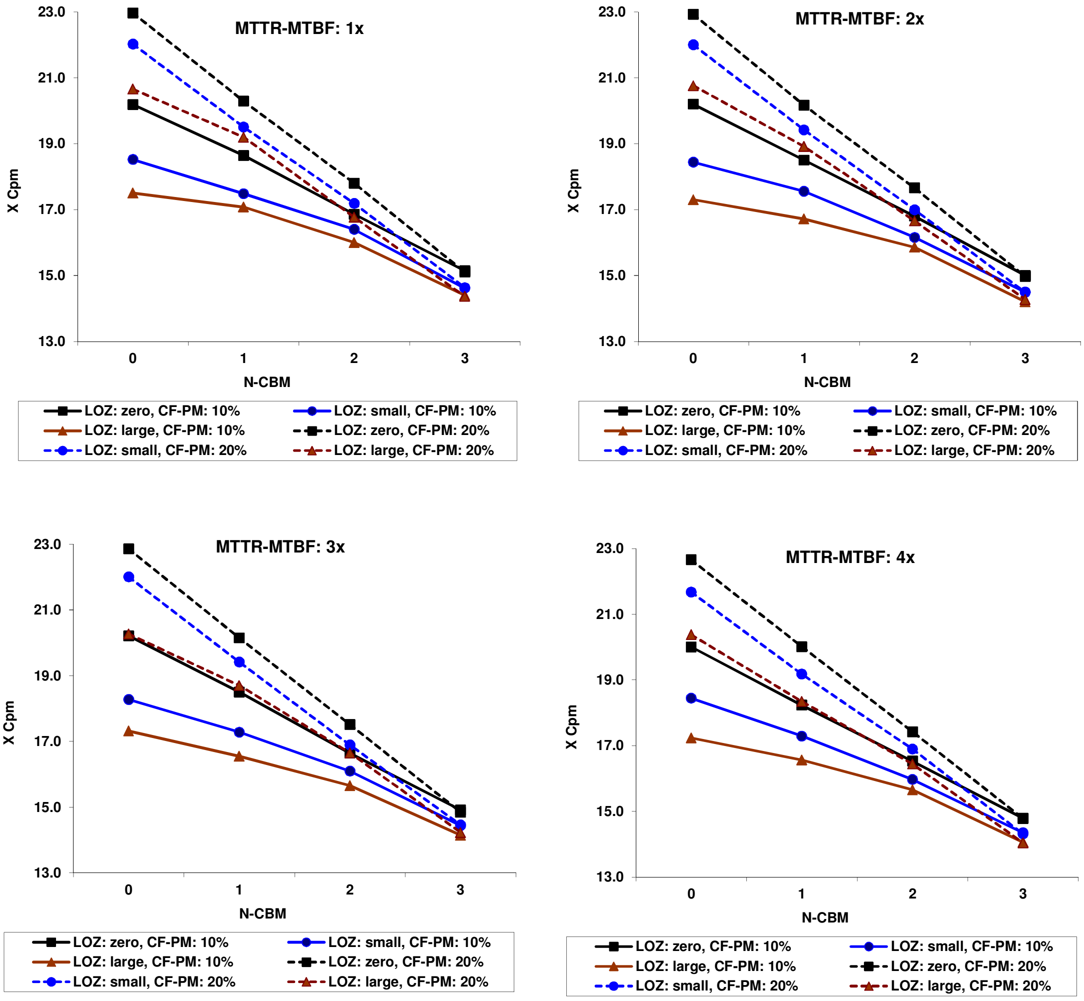

Figure 5-9: The interaction effect of N-CBM, LOZ, CF-PM and MTTR-MTBF ratio on annual maintenance cost

CHAPTER 6

Summary & Discussion

This chapter will summarize the results that have been found throughout this research. We will end the thesis by recommending directions for future research.

6.1 Summary of main findings

This research started with a preliminary goal of finding the reasons of CBM programme failures. Reviewing the existing literature showed that only a limited number of scientific papers have addressed this issue and directly provided evidence for failures of CBM programmes. Besides, the review revealed a gap in the literature regarding CBM evaluation in a plant-wide perspective. It was found that most of the papers analyze CBM effectiveness only for an individual piece of equipment. Further, researchers did not consider the production context, group maintenance and planning aspects of implementation CBM. These findings assisted us to narrow down the focus of this study. The main objective of this research became to study CBM behavior in a multi-component environment. To achieve this goal, three research questions (see Section 1.4) have been posed. These questions are addressed in Chapters 2 to 5. In these chapters, some of the characteristics of multi-component systems were modeled and their effects on CBM have been analyzed. These models provided us with better insight about CBM and revealed how considering a multi-component environment can significantly affect CBM programme justification, which is valuable from both an academic and a practical viewpoint. The details of these findings are discussed in the following subsections.

6.1.1 The effect of production context on CBM

Our first research question was defined to investigate the effect of the production context on CBM. We already have found this as a missing link in CBM evaluation frameworks in Chapter 1. In Chapter 2 and section 5.2 of Chapter 5, we addressed this issue. We showed how using incomprehensive metrics that do not consider the production context can mislead us in a CBM programme justification. A serial production system consisting of two pieces of equipment was modeled. To study the impact of production context, loosely coupled (infinite buffer) and tightly coupled (zero buffer) processes were experimented with. When the PM intervals are not optimal, there are higher chances of failure occurrence within the intervals. We included three different chances of failure occurrence (CFO), four values of corrective to preventive maintenance cost (Cc-Cp) and four MTTR-MTBF ratios as experimental factors. Moreover, we used traditional performance indicators (costs and system availability) and a more comprehensive metric (line efficiency) and compared CBM with age-based and block replacement policies.

It was found that traditional performance indicators do not show the effect of the production context. In all scenarios, CBM had the best performance (the lowest maintenance costs and the highest system availability). Increasing the CFO affected the maintenance costs differently for the various policies. Block replacement was affected most, then age based replacement and it was less influential for CBM. This can be explained by the fact that we assumed ideal CBM, which treats failure events as preventive maintenance actions with the associated costs. Increasing the CFO also had a negative effect on system availability, where the effect was largest under block replacement. Nevertheless, CBM always performed better than the other policies when using the traditional performance indicators maintenance cost and system availability. With these measures, one could thus easily justify CBM programmes.

Line efficiency was the metric that revealed how the production context affects CBM. CBM had the best line efficiency under loosely coupled processes. However, it was difficult to justify CBM under tightly coupled processes. Implementing CBM resulted in blockage and starvation in the system, which negatively affected line efficiency. In this production context, block replacement (BR) had the best performance. Not taking into account the negative effects of blocking and starvation in the justification of a CBM programme will thus result in a too optimistic outcome and this possibly explains the large number of failures of CBM in practice. Further, in the model, the initial investment for CBM has not been considered. Therefore, adding this cost can negatively affect the choice for a CBM programme.

6.1.2 CBM in the context of opportunistic maintenance

Our second question was about CBM effectiveness in the presence of opportunistic maintenance. We answered this question in Chapter 3 and section 5.3. We revealed that the theoretical advantages of CBM for a single component are not necessarily transferable to the plant level and CBM may not be the best policy when we combine it with opportunistic maintenance. A simulation model of a small system consisting of three components in series was built. CBM behavior in an opportunistic and non-opportunistic maintenance context was investigated. In the model the components either used CBM or age based replacement (ABR) policies.

The results showed that implementing CBM for all three components combined with an opportunistic maintenance strategy would minimize maintenance costs, but would not maximize line productivity. In contrast, three components under ABR combined with an opportunistic maintenance strategy would maximize line productivity, especially if the chance of a failure occurring within the PM interval is low, but it would not minimize costs. Opportunistic maintenance synchronized maintenance activities, which was found to improve line productivity and decreased the annual maintenance costs in a serial configuration. Since less maintenance activities could be grouped using CBM, it was less effective in making use of the beneficial effects of group maintenance than age based replacement policy. Implementing CBM for all components minimizes maintenance costs, but some line productivity may be sacrificed. A larger opportunistic zone can improve line productivity in this situation, but whether this is possible depends on the component's degradation function and P-F interval.

6.1.3 Impact of maintenance workforce capacity on CBM benefits

Investigating the effect of CBM on maintenance planning and workforce scheduling was the objective of our third research question. In Chapter 4, the impact of using CBM in serial and parallel multi-component systems was studied and compared with ABR. We demonstrated a situation when companies want to integrate their CBM programmes into their routine maintenance practices. A model of three components in series and parallel configurations was built. And three scenarios that represented different types of maintenance resources and their associated limitations were defined. We studied a situation without worker constraints, a situation with external maintenance workers with a response time, and a situation with a single internal maintenance worker.

The results showed that CBM was not able to group maintenance activities equally well as ABR, resulting in a lower efficiency in the serial configuration. In ideal failure prevention policy without worker constraints and with external workers and a long response time, ABR was more efficient than CBM (especially in serial configuration). With a single internal maintenance worker, the sequential execution of maintenance activities under ABR did not affect the efficiency in the serial system and here CBM performs better. In the parallel configurations, CBM performs better with respect to efficiency than ABR, due to the larger mean time between maintenance activities under CBM. However, with external maintenance workers the efficiency benefits of the smaller average delay times under ABR outweigh the larger average time between maintenance activities under CBM if the response time is large. Therefore, with external maintenance workers and long response time, ABR performs better on efficiency than CBM. With respect to maintenance costs, it was found that CBM performs better than ABR in all situations. The larger average time between maintenance activities under CBM resulted in fewer maintenance activities and thus in lower maintenance costs. The economic gain that was obtained with a larger number of grouped maintenance activities in specific situations was never large enough to reverse this conclusion.

6.2 Discussion

Condition based maintenance uses the operating condition of the component to predict a failure event and therefore tries to avoid any unplanned downtime and unnecessary maintenance activities. There is a lot of interest in academia and practice for this policy. It is even used as a criterion to measure how modern and/or sophisticated a maintenance organization is. However, beside this interest, some researches show that CBM is not always as successful as expected.

Condition based maintenance is an attractive policy in optimizing the maintenance performance for a single component. This contradicts to what operations managers are interested in. They tend to optimize more the performance of the entire asset-system than the performance of single components. In this research we investigated the effectiveness of CBM in the presence of other components and group maintenance strategies. We found that there is no single optimal maintenance policy in a multi-component system. In deciding which maintenance policy to use in practice, several issues play a role. There were always trade-offs between maintenance costs and availability and efficiency.

In Chapter 2 and section 5.2, it is investigated that how the production context can affect CBM benefits. This research direction contributes to both literature and practice. The decision making tools that plants use for maintenance policy selection, are (usually) based on the reliability centered maintenance (RCM) framework. This framework does not consider the production context. Therefore stakeholders cannot see some of the negative side effects (e.g. blockage) of implementing CBM. In studying the role of the production context with respect to the optimal maintenance policy, we created a direct link between selecting a maintenance policy and the line productivity.

The findings in Chapter 3 and section 5.3 provide some insight about CBM behavior in presence of group maintenance (i.e. opportunistic) strategy. We found that implementing CBM prevents sudden failures and consequently minimizes maintenance costs. However, it deprives the companies from performing group maintenance events, which results in lower productivity. The results disclose a set of parameters that are usually neglected in CBM selection decision makings. These parameters are: 1) Accuracy of the PM intervals; 2) The extend of the cost reduction that can be obtained with group maintenance; and 3) The ratio between corrective and preventive maintenance costs.

Chapter 4 reveals the impact of using CBM in a multi-component system with different types of maintenance resources and their associated limitations. When there is a limited maintenance worker capacity, CBM performs better than other policies and grouping maintenance activities is not that beneficial. However, when the maintenance activities are outsourced, CBM is less able to group maintenance activities than other policies, which result in a lower efficiency. Although implementing CBM decreases the maintenance costs, time-based maintenance results in a smoother maintenance plan than CBM. This confirms other researcher's findings and shows why it is difficult to integrate CBM in a plant's maintenance schedule.

6.3 Future research directions

The main body of this research is based on simulation models. These models are digital prototypes of physical models and used to predict what will happen in the real world. Due to time and resource constraints, we added some assumptions and limited our parameters in the models. Therefore, further research can be done in the areas that we did not cover in our models. Moreover, we found a number of issues that need further attention and which could be interesting directions for future research. These issues have been stated in each chapter. Here is the summary of the research opportunities.

First, based on Chapter 2, further research is encouraged to study the effect of in-between buffer sizes, utilization rate and various configurations on CBM's success. This may lead to the development of new metrics to evaluate CBM effectiveness in practice. Second, in Chapter 3 we investigated the potential effects of a CBM implementation on the existing opportunistic maintenance strategy. The model in that chapter can be extended to k-out-of-N systems or different types of failures can be defined. Further, there are various frameworks for opportunistic maintenance strategies. It will be interesting to build models based on other frameworks and rules and compare the results with our findings. Third, based on Chapter 4, an interesting research direction can be to study maintenance outsourcing policies, shutdown scheduling and work force recruitment in the presence of a CBM policy. Indeed considering various failure patterns and complex configurations can improve the mapping of the model to reality. Fourth, only a few case studies have investigated the business side of CBM and have analyzed the influencing parameters in selecting this policy. We believe that more in-depth and longitudinal case studies will provide many insights to academia. This will clarify some of the side-effects of implementing CBM and can assist researchers to develop more realistic decision making frameworks. Finally, CBM is used for many other reasons than availability improvement. Further research is needed to understand these applications and investigate the justification of CBM in other settings.

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Samenvatting (summary in Dutch)

Dit proefschrift onderzoekt strategieën voor onderhoud die zijn gebaseerd op de toestand van productiemiddelen (condition-based maintenance, CBM). Aanleiding voor het onderzoek wordt gevormd door het vermoeden dat CBM in de praktijk weinig wordt gebruikt, terwijl het volgens de theorie veel voordelen biedt.

In hoofdstuk 1 van dit proefschrift wordt de academische literatuur onderzocht. Daaruit komt naar voren, dat CBM inderdaad veel voordelen biedt wanneer men een productiemiddel op zichzelf bestudeert. Men meet dan de beschikbaarheid van het productiemiddel en de onderhoudskosten en concludeert dat CBM goede resultaten heeft. Maar er ontbreekt literatuur die CBM onderzoekt voor productiemiddelen die tezamen een fabriek vormen.

In hoofdstuk 2 van dit proefschrift wordt daarom een (sterk vereenvoudigd) model gemaakt van twee productiemiddelen, oftewel stations, die in serie staan. Er worden twee varianten bestudeerd, namelijk een lijn met een grote buffer tussen beide stations en een lijn zonder buffer. Dit model wordt bestudeerd met behulp van simulatie. Wanneer men hier opnieuw kijkt naar beschikbaarheid en kosten dan is CBM nog steeds een aantrekkelijke strategie. Wanneer men echter kijkt naar de beschikbaarheid van de fabriek als geheel, dan verliest CBM zijn aantrekkelijkheid wanneer er geen buffer is. Anders gezegd, wanneer er een sterke koppeling bestaat tussen productiemiddelen, zodat er een risico is dat het ene station het andere station blokkeert, dan blijkt CBM (in de gekozen experimentele opstelling) niet de beste strategie te zijn.

In hoofdstuk 3 wordt de aandacht verlegd naar het zgn. opportunistische onderhoud. Dit betekent dat men onderhoudswerk groepeert. Wanneer één station op een lijn moet worden onderhouden, kan het verstandig zijn om ook meteen andere stations te gaan onderhouden. Er wordt gekeken naar CBM en een tijds-gebaseerde onderhoudsstrategie (age-based replacement, ABR). Ook hier blijkt, dat CBM weliswaar de individuele stations optimaliseert, maar dat het voor de productiviteit van de fabriek als geheel beter kan zijn om een tijds-gebaseerde onderhoudsstrategie te volgen.

Hoofdstuk 4 van dit proefschrift onderzoekt met name de relatie tussen onderhoudsstrategie en de inzet van onderhoudsmedewerkers in meer detail. Men kan onderhoud laten uitvoeren door een eigen onderhoudsafdeling, maar men kan het ook uitbesteden. Wanneer een productiebedrijf kiest voor een eigen onderhoudsafdeling, is een gespreide vraag naar onderhoud van belang, om leegloop te vermijden. Wanneer men het onderhoud uitbesteedt, is juist vaak groepering van werk van belang

om bijvoorbeeld veelvuldige voorrijkosten te vermijden. Deze problematiek komt aan de orde in hoofdstuk 4, in relatie tot CBM en ABR. Hoofdstuk 4 laat zien, dat CBM voordelen heeft bij een eigen onderhoudsafdeling, terwijl ABR voordelen biedt bij uitbesteden.

Al deze inzichten tezamen geven een goede verklaring voor de vragen die aan het begin zijn gesteld. Met name is duidelijk geworden, waarom CBM voor een productiemiddel op zichzelf een optimale strategie lijkt, maar toch voor een gehele fabriek vaak niet de optimale strategie hoeft te zijn. Daarmee is een bijdrage geleverd aan de theorie van onderhoud die bruikbaar is in de praktijk.